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On the Installation, Operation, Data Reduction, and Maintenance of VHF Electronic Polarimeters for Total Electron Content Measurements,

K. E. EIS,
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FOR THE COMMANDER

John Howard

Chief Scientist

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This report gives practical, explanatory information on the installation, operation, and maintenance of VHF Electronic Polarimeters and on the reduction of data for computations of ionospheric total electron content (TEC). It should be used by Air Weather Service maintenance and observer personnel engaged in making real-time TEC measurements, and it can also be used by personnel engaged in making TEC measurements for scientific studies. Many aspects of the experimental problems associated with TEC measurements are presented in this report.

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NOTE TO POLARIMETER OPERATORS – The authors suggest that those involved in TEC data reduction read Sections 1 and 6 first. Section 6 describes the procedures needed to reduce and interpret TEC data. The other sections might then be read for a fuller understanding of the theoretical and instrumental aspects of TEC observations.

1. INTRODUCTION – Why TEC Measurements

This report is intended to serve as an operational guide for operators of the Air Force's VHF polarimeters for monitoring the ionospheric total electron content (TEC). Because the operators may be unfamiliar with either the theory or instrumentation, this report will attempt to explain, in general terms, polarization, Faraday rotation, and the functions of the polarimeter as well as the basics of its installation, operation, and data reduction. An excellent background report on TEC measurements has been written by Beard.[1] Because some readers will be operating equipment other than one of the Air Force's standardized polarimeters, general instructions for data scaling and conversion have been given for them as well.

Operational USAF satellite-detection radars determine position by the elevation and azimuth of the antenna system and the time from transmission to reception of

(Received for publication 27 May 1977)

1. Beard, E. D. (1975) A Background Report on Total Electron Content Measurements, Air Weather Service (MAC), AWS-TR-75-260.

the radar pulse train. DoD navigational satellite systems determine the position of a user station located anywhere on the globe by using the known position of beacon satellites and the propagation time of the satellite-to-user pulse. The accuracy of these systems, as well as that of certain other VHF and UHF systems, is dependent upon how closely we know the velocity of propagation of the radio wave. This velocity varies, depending upon the medium through which the radio pulse is traveling.

In the above systems, the affecting medium consists of the free electrons in the ionosphere along the line of sight between the radar location and its target or between the satellite and the user location. The number of electrons in the ionosphere varies in a complex manner with time, geographic location, and the state of solar and magnetic activity; this in turn means that the propagation speed of the signal also varies with these parameters. The apparent position, as measured with a UHF system, is, therefore, determined accurately only if we know how the electron content of the ionosphere is changing in time. Without this correction for ionospheric time delay, UHF satellite-detection radars would have mean errors up to several hundred meters in measured target range. Advanced satellite ranging systems used for precise navigation would have range errors, even at L band, of up to a few hundred feet. Ranging systems operated at VHF, sometimes considered for commercial satellite navigation systems, would have ionospheric errors of from 3 to 5 km!

The question is, then, how do we measure the number of electrons along the line of sight? AFGL uses an effect that was first observed by Faraday in his experiments with optics to make measurements of the electron content of the ionosphere. The system developed to take advantage of the Faraday rotation phenomenon was the TEC VHF Polarimeter.

In the sections that follow, the theory of polarization will be outlined, followed by a discussion of the practical problems of polarimeter installation, calibration, operation, and maintenance, and, finally, a section on data scaling and conversion to final TEC values. Also included are several examples of typical data charts recorded during solar and magnetically disturbed conditions.

2. ELECTROMAGNETIC PROPAGATION-POLARIZATION CHARACTERISTICS

Electromagnetic radiation (which includes gamma rays, X-rays, ultraviolet rays, visible light, infrared, and radio waves) has three main characteristics: intensity, frequency, and sense of polarization. The first two are widely known as "brightness" and "color", at least in the visible light wavelengths; polarization on the other hand, is a little-known characteristic.

2.1 Linear Polarization

It is useful to introduce polarization by using vectors. As an example, a plane-polarized radio wave whose wavelength is 10 cm can be vectorially represented as in Figure 1. The Z axis is the direction of propagation or the direction in which the 10-cm-wavelength radio wave is traveling. The wavelength is the distance between adjacent peaks or troughs, as illustrated. The frequency can be easily determined by:

$$\lambda = \frac{c}{f} \tag{1}$$

where λ is the wavelength in meters, c is the speed of light in a vacuum ($c = 3 \times 10^8$ m/sec), and f is the frequency in Hz.

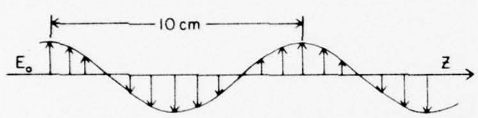

Figure 1. A 10-cm-Wavelength Radio Wave Whose Sense of Polarization is in the Plane Defined by the Surface of This Page

In Figure 1, the intensity is represented by the length of the vector arrows. A longer arrow indicates a more intense radio wave. The polarization of the wave is termed "plane" or "linear polarization" where the wave lies in the plane defined by the surface of the page.

Polarization is determined by the direction of the vectorial arrows. In the case of Figure 1, all the vectors lie in a plane so the wave is said to be plane-polarized. Another plane-polarized wave perpendicular to the first can also be drawn.

In Figure 2, we see two plane-polarized waves, one, $\vec{E}_x$, in the plane of the page, and the other, $\vec{E}_y$, perpendicular to $\vec{E}_x$. $\vec{E}_x$ and $\vec{E}_y$ are the vectorial representations of the two perpendicular waves.

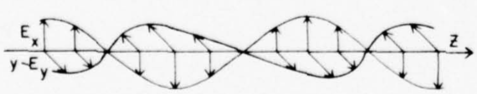

Figure 2. Two In-Phase Plane-Polarized Waves That are Mutually Perpendicular

Here again, the intensity and wavelength are defined as in Figure 1. The observed polarization of this wave, which is really the superposition of two separate wave forms, would not be represented by either the $\vec{E}_x$ or $\vec{E}_y$ component. What

would be detected would be a plane or polarized wave whose plane of polarization is tilted 45 deg to both the X and Y plane. The vectors for this new combined wave can be determined by the vector addition of $\vec{E}_x$ and $\vec{E}_y$. In Figure 3, $\vec{E}_r$ is the resultant vector obtained by the vector equation,

$$\vec{E}_r = \vec{E}_x + \vec{E}_y . \tag{2}$$

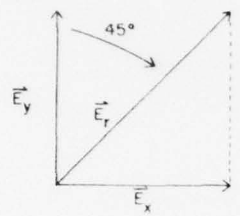

Figure 3. Vector Diagram Showing Resultant Polarization Vector $\vec{E}_r$. Direction of propagation is into the paper

It will be seen that the peaks of the resultant wave occur where $\vec{E}_x$ and $\vec{E}_y$ are at maximum, and the zero point of the resultant is where both $\vec{E}_x$ and $\vec{E}_y$ are zero. This shows that the resultant wave has the same wavelength and waveform as $\vec{E}_x$ and $\vec{E}_y$. Two differences are that the intensity is greater than $\vec{E}_x$ or $\vec{E}_y$, as is observed in Figure 3, and the plane of polarization is different.

The angle of the plane of polarization can be modified by allowing the relative intensities of the X and Y component waves to vary. Only when the X and Y components are equal ($|\vec{E}_x| = |\vec{E}_y|$ at all points) will the plane of polarization be 45 deg. If the components are equal and opposite ($|\vec{E}_x| = -|\vec{E}_y|$ everywhere), you will again get a plane-polarized wave, but one perpendicular to the one where $|\vec{E}_x| = |\vec{E}_y|$.

Figure 4 shows that $\vec{E}'_r$ is perpendicular to $\vec{E}_r$ in Figure 3. If $|\vec{E}_x| = |\vec{E}_y|$, a plane polarized wave at some arbitrary angle results. In Figure 5, where $|\vec{E}_x| = |2\vec{E}_y|$, the angle of the plane would be approximately 55.5 deg from the vertical.

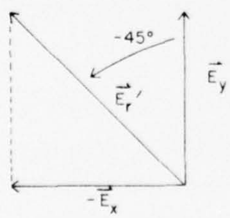

Figure 4. Here the Resultant Vector $\vec{E}'_r$ is Perpendicular to the Resultant Vector $\vec{E}_r$ of Figure 3 Because of the Opposite Sense of the $\vec{E}_x$ Component

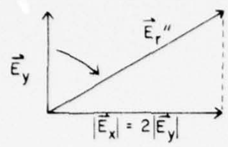

Figure 5. Resultant Vector $\vec{E}_r''$ When $\vec{E}_x$ is Twice the Magnitude of $\vec{E}_y$

2.2 Circular Polarization

Another variety of polarization is circular polarization. To generate a circularly polarized wave, we will again combine two linearly polarized wave forms as we did in Figure 2.

In Figure 6 we see a figure whose only difference from Figure 2 is that the $\vec{E}_y$ maximum has been shifted down the Z axis with respect to the $\vec{E}_x$ maximum. The two wave forms are now 90 deg out of phase. In Figure 6, let us assume for clarity that the sense of the vectors at point A are as follows: $\vec{E}_x$ is toward the top of and in the plane of the paper. $\vec{E}_y$ is perpendicular to $\vec{E}_x$, out of the page. Let us now examine the behavior of the resultant vector $\vec{E}_r$ as we move down the Z axis from point A to point D.

At point A, the resultant vector $(\vec{E}_x + \vec{E}_y) = \vec{E}_x$, since $\vec{E}_y = 0$ and, therefore, $\vec{E}_r$ is in the plane of the page and pointed toward the top of the page. At B, $\vec{E}_x = 0$ so the resultant is off the page. At C, $\vec{E}_y = 0$ and $\vec{E}_x$ is, therefore, toward the bottom of the page, and $\vec{E}_r = (\vec{E}_x + \vec{E}_y)$ or $\vec{E}_r = \vec{E}_x$. Finally, at D, $\vec{E}_x = 0$, so $\vec{E}_y = \vec{E}_r$. Viewing the resultant vector from any point along the Z axis, one sees the head of $\vec{E}_r$ rotate in a circle as it approaches.

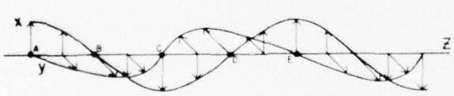

Figure 6. Two-Plane-Polarized Waves $\vec{E}_x$ and $\vec{E}_y$ 90 deg Out of Phase. The phase is represented by the distance from Point A to Point B or for any two adjacent labeled intercepts along the Z axis

It becomes apparent when viewing Figures 7 and 8 that the resultant vector describes a circle when viewed along the axis of propagation. Circular polarization can either be left- or right-handed, depending upon whether the resultant vector is rotating clockwise or counterclockwise when viewed from the direction of propagation back to the on-coming wave. Figure 8 illustrates a left-hand polarization sense according to the IEEE definition. Caution should be taken when discussing polarization sense, because the definition is different for the IEEE and some scientific groups. If $\vec{E}_x$ had been shifted down the Z axis in Figure 6 in the opposite direction, the phase would have been - 90 deg or 270 deg. This would result in a circularly

polarized rotation in a right-handed sense, just the opposite of that depicted in Figures 7 and 8. When $\vec{E}_x$ and $\vec{E}_y$ are varied, the circular, or helical, locus of the resultant vector is distorted and an elipse results.

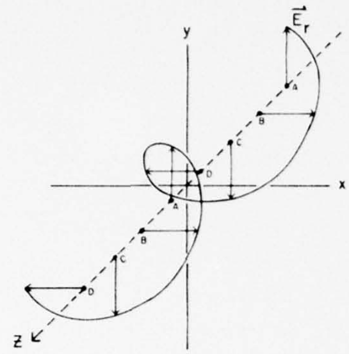

Figure 7. The Locus of the Resultant Perpendicular Vectors Shows as a Helix. Viewed along the Z axis this would appear as a circle

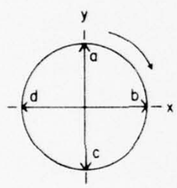

Figure 8. The Locus of the Resultant Vector $\vec{E}_r$ of Figure 7 as Viewed "Head On". The center of the circle would correspond to the Z axis whose direction is out of the paper

2.3 Elliptical Polarization

In Figure 9, $|\vec{E}_y| = |2\vec{E}_x|$. This type of "deformed" circular polarization is called "elliptical polarization". An elliptically polarized wave can be split into a circular and linear component.

Elliptical polarization can also be produced by two wave forms where $|\vec{E}_x| = |\vec{E}_y|$. This is accomplished by letting the phase angle θ take on some value other than 0 deg + 90 deg, or 180 deg. Assuming $|\vec{E}_x| = |\vec{E}_y|$; if ......

θ = 0 deg or 180 deg----------- linear polarization

θ = 90 deg or -90 deg---------- circular polarization right- or left-handed

θ = none of the above ---------- elliptical polarization.

In general, the assumption $|\vec{E}_x| = |\vec{E}_y|$ need not be included in the definition of elliptical polarization, the most common mode of polarization with linear and circular polarized waves as its extremes.

In summary, <u>the phase between two linearly polarized wave forms determines whether one has plane, circular, or elliptical polarization (see Figure 10)</u>.

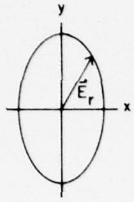

Figure 9. View Identical to Figure 8 Where the Magnitude of the Perpendicular Components $\vec{E}_x$ and $\vec{E}_y$ are Different in This Case $|\vec{E}_y| = |2E_x|$. This is an example of elliptical polarization

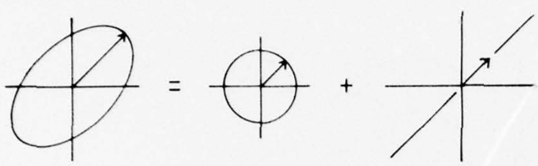

Figure 10. Elliptical Polarization can be Represented by Two In-Phase Vectors, One Linearly Polarized, the Other Circularly Polarized

2.4 The Physical Significance of Polarization

A dipole antenna is a conductive rod, fedby a RF voltage source. When a RF voltage is introduced into the antenna, the free electrons of the metal with which the dipole is constructed begin to vibrate along the axis of the dipole. This occurs because the electrons are negative electrical charges, and when a negative voltage is applied to one end and a positive to the other end of the dipole, the electron is repelled by the negative and attracted to the positive end. Since the voltage on one end alternates from positive to negative, the electron is alternately attracted and repelled by that end. The result is many electrons vibrating in rhythm with the impressed voltage. Generally, when a charged particle accelerates it generates electromagnetic energy. The electrons in the dipole are moving to the right, then they stop, then they move to the left and stop, etc. This changing direction of the vibrating electrons is an acceleration; therefore, an electromagnetic wave is generated.

Figure 11 illustrates the plane-polarized wave developed by the horizontal orientation of a dipole. The frequency of the radio wave in space corresponds to the frequency of the RF voltage source driving the antenna.

Figure 12 illustrates the wave strength of the signal generated by a dipole with respect to the dipole's orientation. θ is the angle from a plane perpendicular to the dipole axis where the signal strength is maximum. Note that the signal falls to zero along the axis of the antenna ($\theta = \pm 90$ deg). In general, any simple dipole will transmit a linearly polarized wave whose orientation is parallel to the axis of the dipole.

The receiving antenna utilizes this same physical mechanism in reverse. For reception, the electromagnetic wave passing by the antenna excites the loosely bound

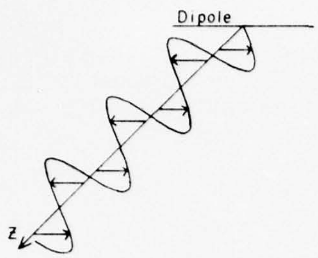

Figure 11. The Plane Polarized Wave Launched by a Horizontal Dipole

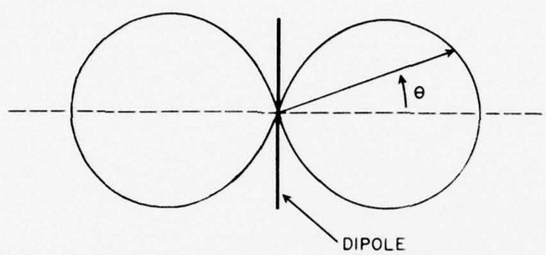

Figure 12. Wave Intensity of Dipole in Plane of Dipole. For a true three dimensional representation of the signal strength, the lobe pattern should be rotated about the dipole

electrons of the antenna which in turn produces a voltage across the dipole. When a linearly polarized signal is sensed by a properly aligned dipole, the orientation of the wave's and the dipole's polarization are parallel. This assures that more free electrons vibrate in sympathy than would be the case if the orientations of wave and dipole were perpendicular. In the perpendicular case the additive effect would only occur across the thickness of the dipole rod.

Figures 13 and 14 show an antenna aligned to take advantage of the signal's sense of polarization. Since all TV signals in the United States are broadcast with horizontal polarization, all TV antennas are aligned horizontally. In the measurement of total electron content (TEC), the polarimeter continuously measures the sense of the received linear polarization. The amount of rotation or twisting that the orientation of the linearly polarized wave undergoes from the satellite to the received ground station is proportional to the TEC. This relationship, and how to make the measurement of the changing sense of polarization, will be fully described in the following sections.

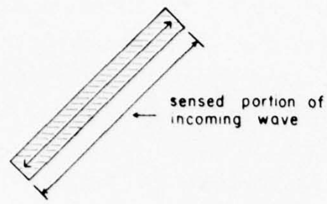

Figure 13. The Arrow Inside Box Represents the Resultant Vector of a Radio Wave. The box itself is a graphical representation of the antenna's sensitivity to a linearly polarized wave. In this example the antenna orientation allows 100 percent of the radio wave to be sensed

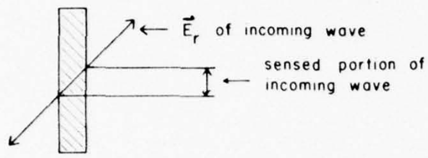

Figure 14. An Antenna Misaligned With Respect to the Radio Wave's Sense of Polarization. In this case the portion of the vector actually sensed is about 25 percent. Note that the shaded box does not represent any physical dimension of the box. The shaded box is only used to represent the ratio of parallel vs perpendicular antenna sensitivity to a polarized wave when the antenna is aligned vertically

3. WAVE PROPAGATION AND FARADAY ROTATION

3.1 The Index of Refraction

The velocity of electromagnetic waves is given by:

$$c' = \frac{c}{n}, \tag{3}$$

where c is the speed of light in a vacuum ($c = 2.997925 \times 10^8$ m/sec) and n is the index of refraction of the medium. In quartz, where $n = 1.250$, the speed of light is only 80 percent of the speed of light in a vacuum.

3.2 Ionospheric Time Delay

The time delay in the ionosphere, mentioned in the introduction, occurs because the index of refraction is larger than unity. Thus,

$$\Delta T = T' - T \approx \frac{ndL}{c} - \frac{dL}{c}, \tag{4}$$

where ΔT is the time delay and dL is the path length through the ionosphere.

After substitutions and approximations are made for n for the UHF domain, we see that the positional error, Δr, can be expressed as:

$$\Delta r \approx \frac{40.3}{f^2} \int N dL, \tag{5}$$

where f is the frequency being monitored in Hertz, and the term $\int NdL$ is the number of electrons along the path, L, made of small path lengths, dL. N is the number of electrons per cubic meter in the increment of length dL, where dL is along the line of sight. The integral $\int$ means we sum all the dL's from observer to satellite. For a frequency of 1600 MHz, a 5.25 nsec delay will be produced by a TEC of 10^{17} electrons in a 1-m^2 column from receiver to satellite. At 100 MHz, 10^{17} el/m^2 will produce a time delay of over 1 μsec.

Since the position delay, Δr, is the distance that an electromagnetic wave travels in the delay time,

$$\Delta r = \Delta T \cdot c \tag{6}$$

or

$$1.57 \text{ m} = (5.25 \times 10^{-9} \text{ sec}) \times (2.99 \times 10^{8} \frac{\text{m}}{\text{sec}}) .$$

3.3 Birefringence and the Faraday Effect

It has been shown that the number of electrons along the path of propagation will change the medium's index of refraction and thus retard the wave with respect to a wave in a vacuum. If the medium containing electrons also contains an ambient magnetic field, another effect results. Since electromagnetic waves propagate through a medium containing electrons by exciting the electrons into sympathetic motion, they re-radiate at the same frequency. Any force impeding the vibration of the electrons will thus affect the wave.

A magnetic field exerts such a force when charged particles cross field lines. This force F can be represented by the vector equation,

$$\vec{F} = q\vec{v} \times \vec{B} ,$$

where q is the electric charge, $\vec{v}$ is the electron's velocity vector, and $\vec{B}$ is the magnetic field strength vector. The X is the vector cross product that can be thought of as a times sign when $\vec{v}$ and $\vec{B}$ are perpendicular. The direction of $\vec{F}$ is perpendicular to both $\vec{v}$ and $\vec{B}$ when $\vec{v}$ and $\vec{B}$ are mutually perpendicular. The three vectors have the geometry of the three edges at the corner of a box. The macroscopic effect is that an electron moving across field lines will be deflected into a circular path. If there is any velocity component of the electron parallel to the field, it will not be affected, so the electron will follow a helical path. Figure 15 illustrates how this electron's path is affected by a magnetic field.

Another way this preference for direction exhibits itself is via the index of refraction. If you were to pass a plane-polarized electromagnetic wave through a

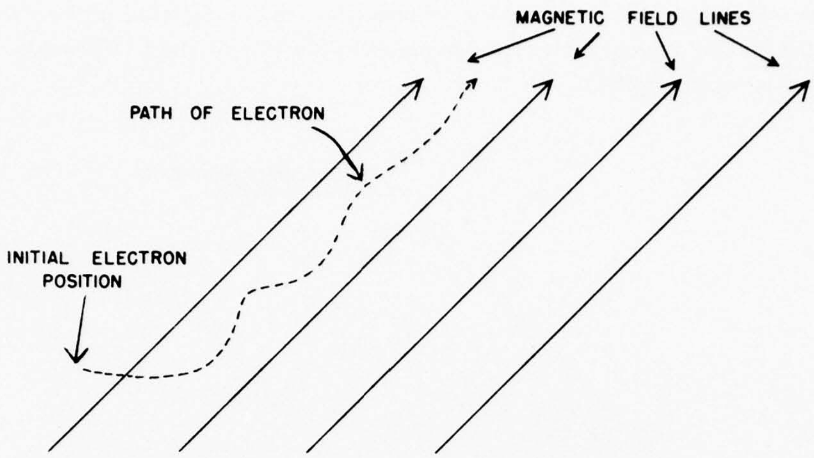

Figure 15. Motion of an Electron in a Magnetic Field

region containing electrons imbedded in a magnetic field, you would be able to measure different propagation speeds as the orientation of the magnetic field and direction of propagation were varied. At VHF or higher frequencies, the additional time delay produced by the magnetic field is generally negligible. Thus Eqs. (4) and (5) are still correct in the presence of a magnetic field. The important difference is that the refractive index in the presence of a magnetic field is dependent on the direction of propagation. Any propagation region that has two different indices of refraction is called birefringent.

A linearly polarized wave can be broken into two components, one parallel and one perpendicular to the ambient magnetic field the wave is passing through. Remember that breaking the wave vector up is the reverse of what was done in Figure 2. Figure 16 shows the wave vector $\vec{E}_r$ being split into a parallel component $\vec{E}_B$ and a perpendicular component $\vec{E}_p$. The $\vec{E}_B$ component is unaffected by the magnetic field. (B is the symbol used for the intensity of a magnetic field.) This means that the index of refraction for the $\vec{E}_B$ component is the same as it would be if the magnetic field were absent. On the other hand, the component $\vec{E}_p$ is affected by the magnetic field. The stronger B becomes, the larger the index of refraction. The result is that two modes of polarization are moving at different speeds, which causes the phase angle between them to shift.

As the phase angle varies, the sense of polarization changes, thus causing the resultant vector to rotate, as in circular polarization. The effect is a plane-polarized wave rotating as it propagates through the electrons and magnetic field. As a linearly polarized wave passes through a medium containing electrically charged

particles (electrons in the case of the ionosphere), the orientation of the wave rotates when an ambient magnetic field parallel to the line of sight is present. This effect is the Faraday effect.

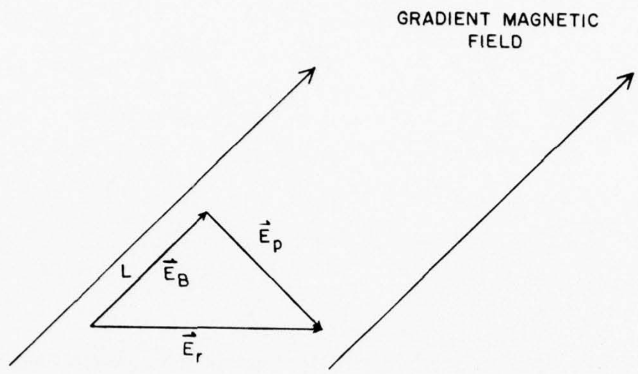

Figure 16. The Resultant Vector $\vec{E}_r$ Can be Broken Into Two Components, One of Which is Parallel ($\vec{E}_B$) and One Perpendicular ($\vec{E}_p$) to the Ambient Magnetic Field

On the other hand, if a wave moves through ambient electrons and a magnetic field where the field lines are perpendicular to the line of propagation, the behavior of the polarization is much more complex; it will not be discussed here.

3.4 The Faraday Equation

This effect was first observed in an optics laboratory experiment by Faraday and was, therefore, dubbed "Faraday Rotation". As one might expect from the description, the amount of rotation is dependent upon the intensity of the magnetic field B, the angle between the ray direction and the magnetic field orientation, the length of the path in which the effect occurs, and the electron density. Stated as an equation, the Faraday Effect is:

$$\Omega = \frac{K}{f^2} \int B \cos \theta \, N dL, \tag{7}$$

where

Ω is the amount of Faraday rotation in radians (1 radian = 57.3 deg),

K is a constant that includes the electron's charge and mass, the velocity of light, and other physical constants that appear in the derivation of the equation (for our purposes, $K = 2.36 \times 10^{-5}$),

f = frequency of wave (in Hertz),

B = magnetic field intensity in gammas (1 gamma equals 10^{-5} gauss),

θ = angle between the direction of propagation and the magnetic field direction, and,

$\int NdL$ is again the TEC along the line of sight (in electrons per meter^2).

In summary, the positional error Δr, which is the value we wish to know, is dependent upon $\int NdL$ [see Eq. (5)]. This value can be calculated by measuring the Faraday rotation [see Eq. (7)]. For a satellite-to-ground path where B and cos θ are known, we can directly calculate Δr from the TEC.

To measure Ω we need to know the initial and final sense of polarization of the satellite signal. By using a geosynchronous satellite with a transmitter dipole antenna of known orientation and a device on the ground to measure the final sense of polarization, we can ultimately determine the delay. Let's now look at the instrument that measures the polarization–a polarimeter receiver whose antenna is designed to detect the sense of polarization of the incoming wave (see Figure 17).

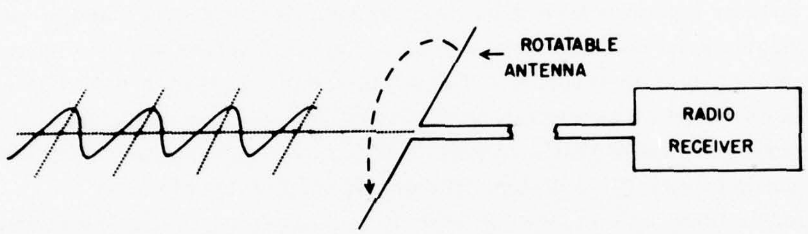

Figure 17. A Rotatable Dipole Antenna Aligned for the Maximum Reception of an Incoming Plane Polarized Wave

4. POLARIMETER – Methods of Operation

Before we address the specifics of the polarimeter used by AWS, let us first look at the most common types of polarimeters and their method of operation.

4.1 Mechanically Rotating Polarimeter

A simple polarimeter is a rotating antenna. As the antenna rotates, there will be a maximum reading at the output of the receiver when the plane of the dipole and the plane of polarization of the incoming wave coincide(see Figures 13, 14, and 17). The orientation of the antenna at this maximum gives the sense of polarization. An automatic polarimeter can be constructed by placing the antenna on a rotating platform. Knowing the rate of rotation and the absolute sense at any arbitrary point gives you a sinusoidal readout whose maxima correspond to the sense of polarization as time progresses, and this readout can be used to measure Faraday

rotation. The major drawback of a rotating platform is the necessity for high mechanical reliability and the fact that measurements of the received angle are only made once every 180 deg of rotation. Because the antenna is rotating, there must be a slip-ring contact or inductive coupling somewhere between the antenna and the receiver. Figure 18 illustrates a chart recording output from a Yagi antenna rotating at 1/2 rpm. Note that the received polarization angle is measured only at the minima or nulls of the incoming signal amplitudes, which occur approximately once each minute.

A mechanically rotating antenna that spins at a 60 rpm rate, and which, therefore, gives two nulls per revolution for a measurement rate of two values per second, has been developed by Titheridge.[2] His polarimeter uses an electronic means, called a phase detector, to measure the time difference and, hence, the polarization, between the received null and the reference point that occurs once per revolution.

4.2 Electronically Switched Polarimeter

Still another type of polarization measurement device can be made by using several linearly polarized antennas aligned at different angles and by electronically switching among them in sequence. The advantage of this type of polarimeter is that the dipole selection switch can be electrical and need not be mechanical. Figure 19 illustrates a set of four antennas used in such a polarimeter. The output for the antennas in Figure 19 would look like that presented in Figure 20.

The output takes on an incremental form because there is no position between antenna 1 and 2 or between 2 and 3, etc. The output would have more closely spaced increments if more than four antennas were used. To measure Faraday rotation it is necessary to measure the change in polarization sense with time.

In Figure 21, the sense of polarization is changing in time. In set a, the sense of polarization corresponds most closely with antenna 3. In set b, the polarization sense is between antennas 3 and 4, and in set c it corresponds to antenna 4. Here you can actually see the ionosphere change the sense of polarization of the incoming signal. The negative tick between 1 and 4 is a zero-degree reference, by which the degree of rotation can be scaled, knowing there are 180 deg or π radians of rotation between ticks. Between set a and c of Figure 21, there is a shift from antenna 3 to antenna 4 of 1/4 of the 180 deg. This implies a 45 deg or $\pi/4$ radian Faraday rotation in the time scale represented.

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2. Titheridge, J.E. (1966) Continuous records of the total electron content of the ionosphere, Journ. Atm. and Terr. Phys., 28(No. 12):1135-1150.

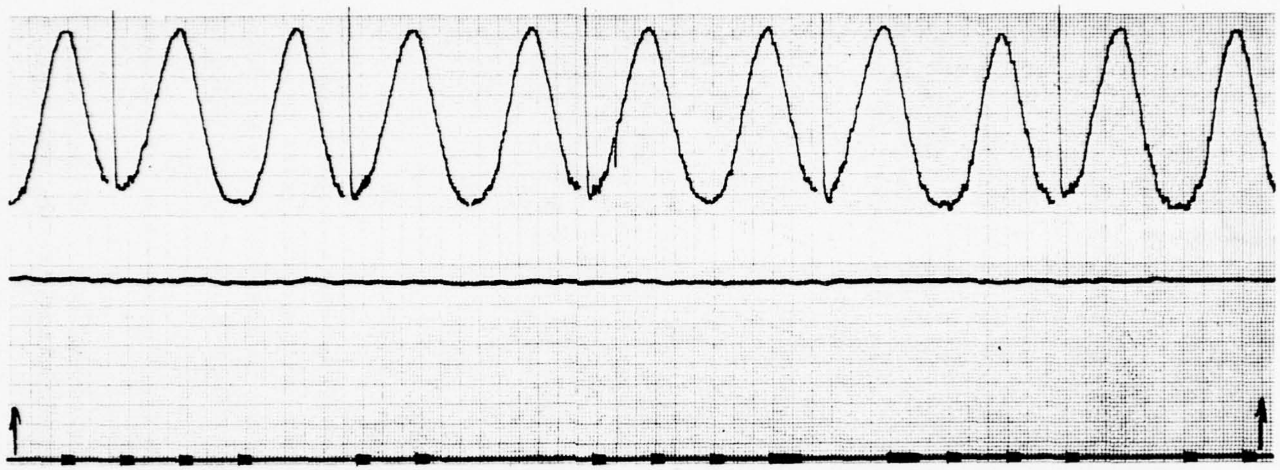

Figure 18. The Top Channel is the Amplitude of the Receiver Output as a Yagi Antenna is Slowly Rotated. Each 360 deg of rotation, an off-scale mark on this channel indicates an absolute sense of antenna orientation. Peaks and nulls in received signal occur as the Yagi antenna is alternately aligned and orthogonal to the orientation of the incoming linearly polarized signal.

The middle channel is the output of a separate receiver that uses a circularly polarized receiving antenna. This antenna gives constant output amplitude with any orientation of the incoming linearly polarized signal and is used to monitor amplitude scintillations of the incoming signal.

The bottom pen contains timing information.

Figure 19. Orientation of Four Dipoles Used in an Electronically Switched Polarimeter

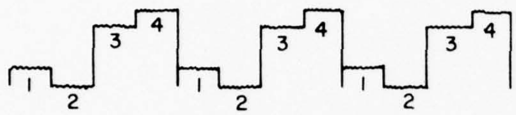

Figure 20. The Output of the Dipole Array of Figure 19. The sense of polarization was approximately 120 deg from the horizontal

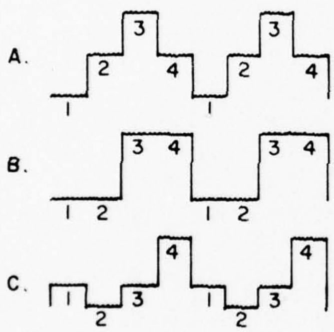

Figure 21. A Hypothetical Measurement, in Time, of Polarization With the Array Illustrated in Figure 19. The sensed wave's polarization is rotating from 90 deg in A to 112 deg in B to 135 deg in C. If the time between A and B was 1 min, the change in polarization would be 22.5 deg/min

It becomes readily apparent that although this technique will work by directly recording the outputs in sequence on a chart recorder, it has several disadvantages:

(1) It is very tedious to scale from the reference tick to the observed maximum. This would be even worse if the polarimeter scanned through all four antennas 1800 times a minute.

(2) The accuracy of reading the incoming polarization is approximately ± 22.5 deg.

(3) It is easy to lose track of which rotation you are on, since the Faraday rotation is capable of rotating the incoming signal several full turns.

4.3 Miscellaneous Polarimeter Types

There are several other types of polarimeter schemes that have been proposed for Faraday rotation measurements. These include phase comparison of left and right circular polarization antennas (as in the case of the Teledyne polarimeter),[3] mechanical switching among several antennas aligned at equally spaced angular intervals, and mechanical switching between two antennas aligned at a 60 deg angle. Also, mechanical goniometers and audio sine-cosine modulation techniques have been used to simulate a single rotating Yagi. Our description will be limited to the electronically rotating antenna described below.

4.4 Electronically Rotating Antenna

A method of electronically measuring the received polarization angle has been developed by Antoniadis;[4] this method uses two antennas aligned at 90 deg to each other to simulate four antennas oriented at 45 deg, as shown in Figure 19. There is an electronic switch that sequentially measures the amplitude of the incoming linearly polarized wave at 45-deg intervals of polarization. This sequential sampling is done at a low audiofrequency rate, and after the weak RF signal is amplified in a receiver, the audiofrequency is detected and filtered through a narrow bandpass filter tuned to this audio-switching frequency. The combination of the square law detection of the audio signal and the filtering of the fundamental audio-switching frequency gives the equivalent of a single antenna that is spinning at the audio rate. Then, by means of an electronic phase detector, the phase difference between the switching frequency and the audio filter output is measured. This type of polarimeter is the one that is used in the AWS real-time TEC monitoring network. It will be described in more detail in later sections of this report.

5. POLARIMETER INSTALLATION

5.1 Site Selection

The radio signals used for the Faraday rotation measurements of TEC are transmitted from geostationary satellites located approximately 25,000 miles away from the ground receiver location. The nominal power transmitted from the satellite is generally about one watt, and the antenna gain of the satellite VHF

3. Hicks, P.A. (1972) A low-cost, all electronic Faraday notation polarimeter, Proceedings of the Symposium on the Future Application of Satellite Beacon Measurements, Published by the University of Graz, Austria, Editor, R. Leitinger.

4. Antoniadis, D.A. (1974) A novel method for measuring the polarization angle of satellite radio waves, IEEE Trans. on Aerospace and Electronic Systems, AES-10(No. 4):510-515.

antenna is minimal. Thus, the signal to be received at the ground is not strong; therefore, if successful TEC measurements are to be made, the receiving site must be chosen with weak signal reception in mind. Avoid a location near large power lines. Also, avoid co-location with any nearby RF generating sources such as electric motors or radio transmitters. Avoid a location near a road, an aircraft runway, or a taxi strip. The polarimeter electronics must be in a building having a relatively constant temperature environment. Avoid an inside location where the equipment would be in direct sunlight, even though the building is air conditioned.

5.2 Antenna Placement

Having chosen a site relatively free from local RF interference, it is very important to have an unobstructed view from the antenna to all possible positions of a geostationary satellite. For a northern hemisphere station, a geostationary satellite can be viewed from the east at a low elevation angle, to the south at its maximum elevation angle, and around to the west again at a low elevation angle. These directions must be free of obstructions for satisfactory polarization recordings to be made.

The satellite antenna used at most locations consists of a crossed Yagi type on a heavy-duty mount and wooden base. The complete assembly should be mounted on the ground rather than on the edge of a rooftop, as the higher elevation of the rooftop mounting would contribute to erroneous *ground-reflected polarizations*, which are minimized when the antenna is mounted at ground level.

If you are certain that the satellite you will be monitoring will always be at an elevation angle higher than approximately 40 deg, then the rooftop mounting will be satisfactory. At high satellite elevation angles, the ground-reflected signal becomes negligible. Again, make certain that the antenna system has a satisfactory free and clear view to all possible satellite directions. This means that the antenna must be mounted next to the south side of a building for northern hemisphere stations. Make certain that no other obstructions, particularly those having large areas of metal or wire, are near the antenna.

Our last antenna-mounting precaution is: since the signals from the satellite are very weak, it is important to mount the antenna so that the length of the coaxial cable to the polarimeter receiver is no more than approximately 100 ft (30 m). The shorter this cable is, the better the signal will be.

5.3 Crossed Yagi Antenna Positioning

The crossed Yagi antennas, the aluminum mount, and the wooden base are shown in Figure 22. Figures 23 and 24 show the details of the base and aluminum mount used at many of the sites. Note in Figures 22 and 23 that the support wire

turnbuckles have not yet been tightened nor have the lag bolts been fastened. In Figure 24 the details of mounting the antenna boom to the aluminum mount are shown. Be certain to rotate the antenna boom so that the two Yagis each have their elements aligned at 45 deg to the vertical. This is to equalize the effects of ground reflections on the two antennas. Also shown in Figure 24 are the details of how to position the antennas in azimuth and in elevation angle. Note that there are a series of holes drilled at 10-deg increments in the azimuth rotation platform and in the elevation support plate. There are two holes or positions on the stationary portions of the mount (not visible in figure) in which the fastening bolts can be placed, thus giving both elevation and azimuth pointing capability at 5-deg intervals. After the actual azimuth and elevation angle of one set of holes are found, the others can be determined by counting off in 5-deg intervals from that position. The correct pointing angles to the geostationary satellite are known, and the set of general look angles furnished each station at time of installation can be used for antenna pointing information.

One additional point about the antenna mount—the mount and base were designed with the extremes of wind velocity in mind. Be certain to position the counterweight properly and to tightly fasten the guy cables and the lag bolts. If the antenna mount and base are installed properly, the installation should withstand hurricane force winds without damage. If not, even moderate storms can cause fatigue of some of the welds.

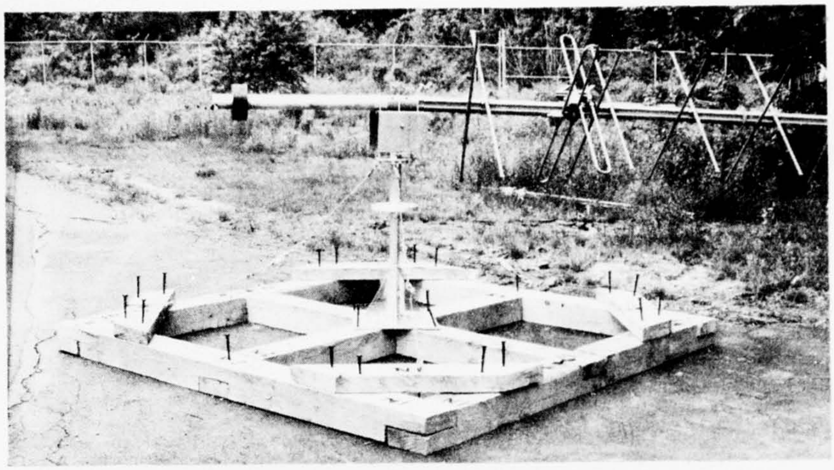

Figure 22. Complete Crossed Yagi and Mount Assembly

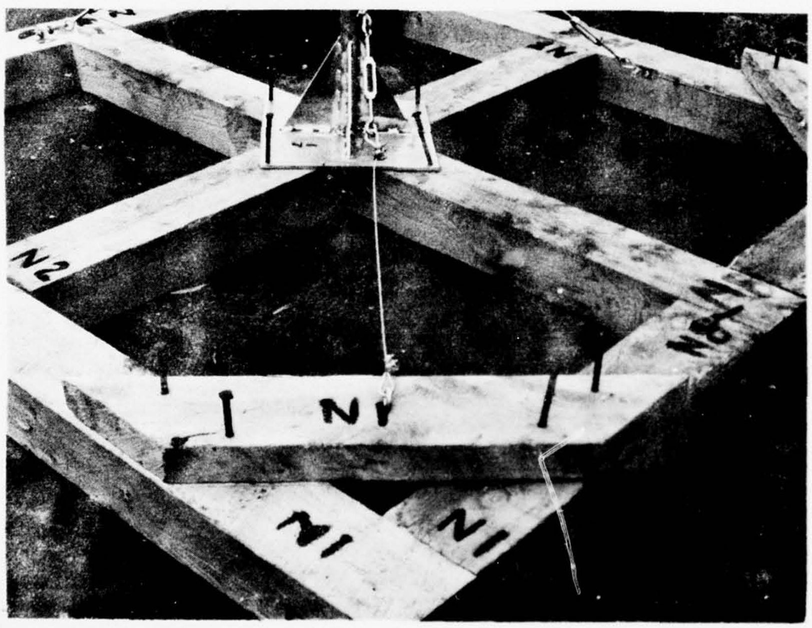

Figure 23. Detail of Antenna Base

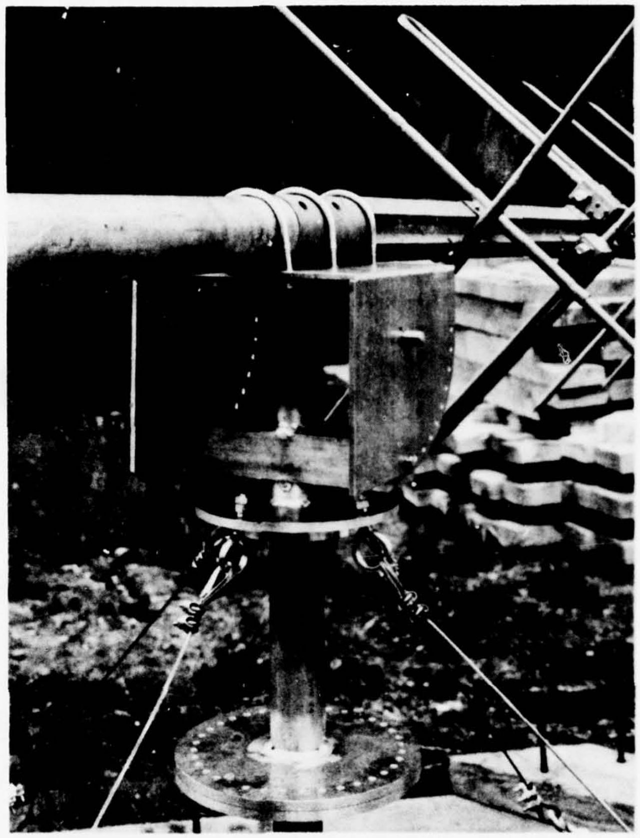

Figure 24. Detail of Elevation Angle Adjustment on Antenna Base Mount

5.4 Antenna and Transmission Lines

The Yagi antennas shown in Figure 22 are each made up of a driven element folded dipole with a built-in balun, a reflector element, and several director elements. Both antennas share the same boom; therefore, one must be mounted farther forward on the boom than the other one. Since one of the antennas is physically and electrically closer to the satellite than the other one, this electrical phase difference must be compensated for. The Yagi that is closer to the satellite must have a longer cable connected to it to compensate for its closer electrical distance to the satellite. For the standard Taco Corp. antennas used at most installations, this additional cable length is 2-3/8 in. (6 cm).

5.5 Physical Location of Equipment

In locating the equipment rack that houses the polarimeter receiver, calibrator, chart recorder, and primary line voltage regulator, avoid locations where sudden changes in temperature may occur, such as near a doorway or near a window where the sun could change the equipment operating temperature. Mount the equipment at convenient heights in the equipment rack, especially the chart recorder that will be used continually for reference to the TEC values. Choose a room where there is not a great deal of acoustic noise or where personnel passing through might be tempted to change an equipment knob setting. Remember, the equipment will be in continuous use and the data scaling from the chart recorder will be carried out continually, so try to maximize operating efficiency.

5.6 Diode Switch RF Connections

The diode switch is an electronic means of simulating four Yagi antennas out of two antennas, as described in Section 4.4. The four equivalent antennas that are simulated are as shown in Figure 18 and are sequentially selected as shown in Figure 25. The waveforms of the switching voltage to the diodes that accomplish this sequence are shown in Section 7.

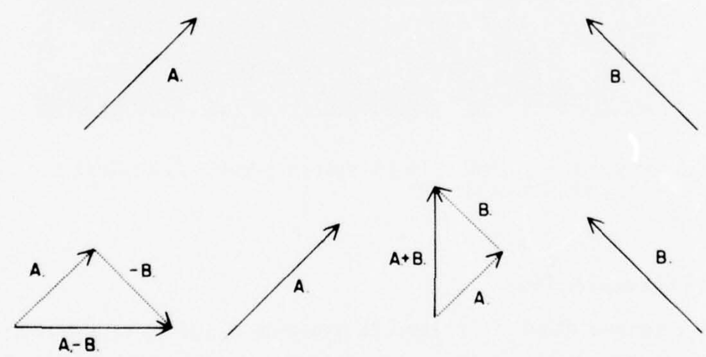

Figure 25. The Vectorial Addition Used in an Electronically Switched Polarimeter With Yagi Antennas of Polarized Sense A and B, to Obtain A - B, A, A + B, and B Orientations

When installing the polarimeter, be sure that the coaxial antenna cables are properly connected to the RF switch. As you stand behind the antennas, looking along the boom towards the satellite, the Yagi that is at a 45-deg counterclockwise direction with respect to the horizontal must be connected to the RF switch input labelled "A". On the AFGL-built polarimeters, this input may be labelled "SINE".

This is shown in Figure 26. Connect the other antenna cable to the RF switch input labelled "B" or "COSINE". Place permanent labels on the two coaxial cables after you determine to which switch input they must be connected, because when calibrating the equipment these cables must be disconnected from time to time and they must not be inadvertantly interchanged.

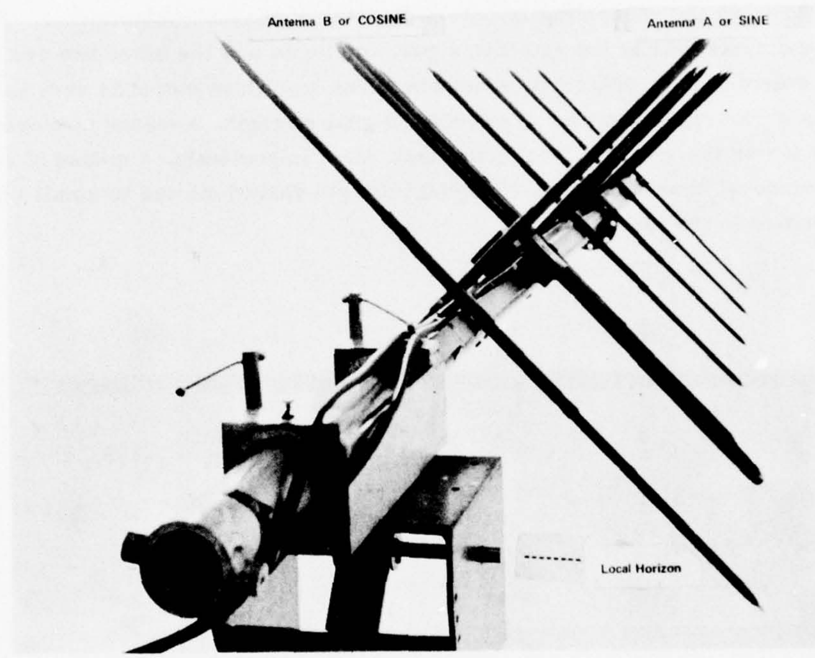

Figure 26. The Proper Orientation for Determining the "A" and "B" Antenna

Connect the switch drive cable (a small, multi-conductor cable from the output on the back of the polarimeter chassis) to the receptacle on the RF switch box. The RF output of the diode switch goes to the polarimeter receiver input on the commercially designed units that have built-in RF converters.

When using the AFGL-built polarimeter, connect the RF output of the diode switch to the input of a separate RF converter that converts the satellite signal from the VHF satellite transmitting frequency to a frequency either in the 28 MHz or 10.7 MHz range, depending upon the type of RF converter used. The output of the RF converter at one of these intermediate frequencies is connected to a high quality

communication receiver, generally an R-390A receiver, which is tuned to the exact converter output frequency.

5.7 Polarimeter Receiver Output Connections

After the antenna cables have been connected at both the antenna and RF diode switch ends and the output of the diode switch has been connected to the converter or receiver, as appropriate, only the polarimeter outputs remain to be connected. Figure 27 shows the connecting layout on the back of the Aldi polarimeter. There are three outputs; one is the satellite signal amplitude and the other two are identical, but out-of-phase, polarization outputs. The amplitude output is very important; it is a continuous monitor of received signal strength, a means of monitoring interference on the satellite frequency, and, most importantly, a means of measuring the temporal characteristics of signal strength variations due to small scale irregularities in the ionosphere.

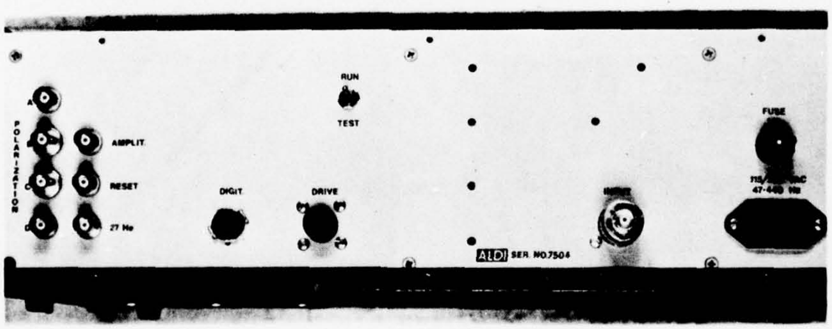

Figure 27. Detail of Back Panel of Aldi Polarimeter

The two out-of-phase polarization outputs are used so that when one channel is at the edge of its chart span and is attempting to switch back to the opposite end of its span, the other channel is in the middle of its scale. This complementary behavior of the two phase channels allows the data to be accurately and easily scaled, even though the polarization may be rapidly changing and reversing direction.

To properly display and record the amplitude and the two polarization outputs, a chart recorder having at least three channels must be used. The polarimeter reference channel—the one labelled "B" in the Aldi commercial unit and the one labelled "180°" on the AFGL unit—should be connected to the channel nearest to the edge of the chart that has the time code marks, since the polarimeter reference channel is the chart channel from which TEC measurements are scaled each 15 min. Figure 28 illustrates the data output from the three-channel recorder, and Figure 29 shows the Aldi polarimeter panel layout. This placement of the polarization reference channel minimizes chances for timing errors in data scaling. Figure 29 illustrates a typical polarimeter panel layout minus the chart recorder.

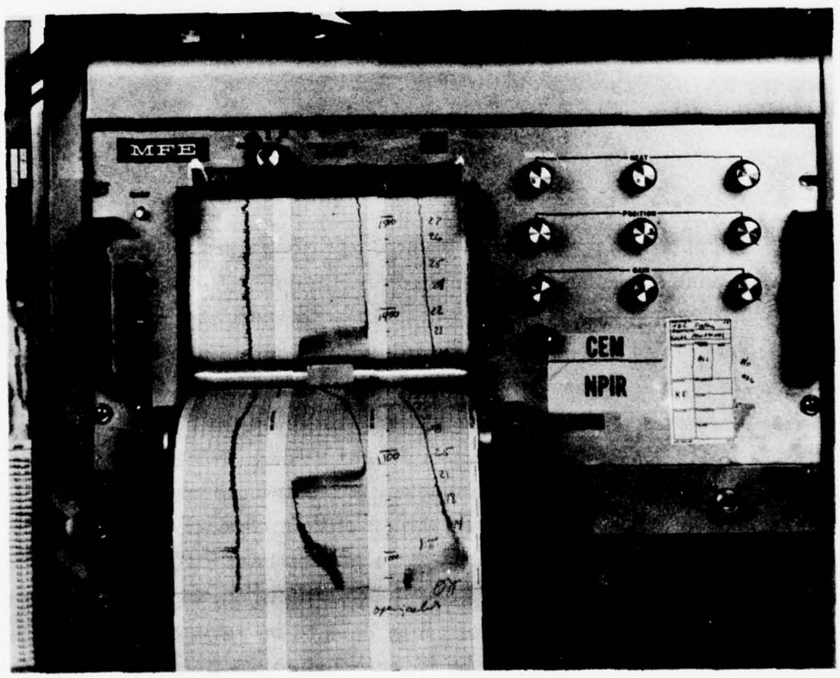

Figure 28. Chart Recorder Used for Polarimeter Recordings. Note the placement of the recordings on the three channels

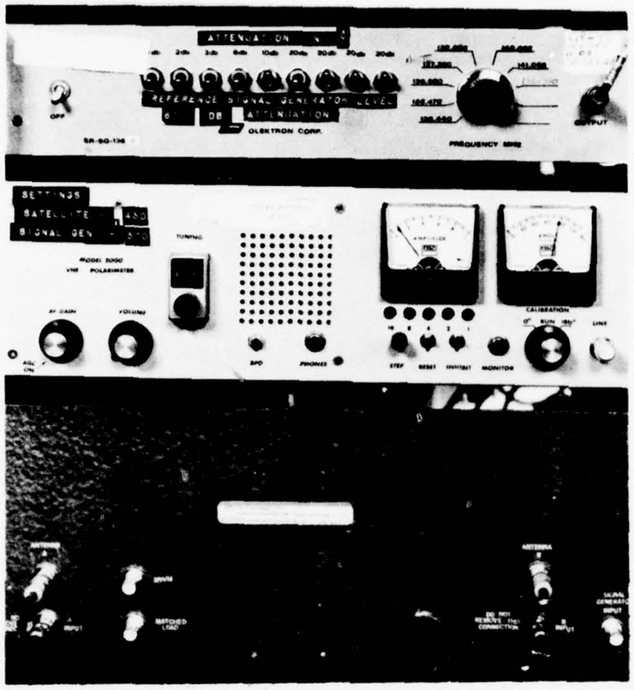

Figure 29. A Typical Polarimeter Panel Layout. The top box is the reference signal generator used in calibrations, the middle box is the polarimeter main frame, and the bottom "box" is the antenna calibration switching panel

The orthogonal polarization channel should be connected next to the reference polarization channel, because they are used together to determine the polarization during times of rapid polarization change. The amplitude channel should be placed farthest away from the time code edge of the chart. Samples of chart recordings are shown in the figures of Section 6.9.

In initially hooking up the polarimeter outputs to the chart recorder, it is important that upscale values all have the proper sense. When looking at a section of record while viewing the time code marks, with time increasing from left to right, the two polarization channels and the amplitude channel should display increasing values in the direction away from the edge of the chart that has the time code. To accomplish this in the initial equipment installation, the wires that go to the recorder chart galvanometer amplifiers may have to be reversed. An upscale reading on the amplitude channel can be determined easily by performing an amplitude calibration as described in Section 6.3. The direction of increasing Faraday rotation can initially be determined by observing the change in the two polarization channels during the sunrise period when the TEC is increasing rapidly.

It should be noted here that the directions of the Faraday rotation changes on the phase channels can be reversed simply by reversing the coaxial cable connections to the RF switch; however, this is the incorrect method and must not be used because the reference channel zero value and scaling procedures will no longer be correct if the sense of rotation is reversed in this manner.

6. OPERATIONS AND DATA REDUCTION

6.1 Introduction

The basics of TEC operations and data reduction for the AWS operated station can be found in AWSR 105-33,[5] Chapter 5. This section will more fully explain the topics contained in that regulation and can be used as a procedural and "how to" supplement to it. This section will also explain, in detail, the procedures for computing the conversion between Faraday rotation and TEC, which are done automatically for the AWS observers by means of the monthly conversion tables sent to each station. Other experimenters can determine their conversion factors, as described in Section 6.5.

6.2 Polarimeter Phase Calibration

Both the reference phase channel and the orthogonal (out of phase) channel must be calibrated for a relative chart deflection of 45 divisions out of a possible 50 full-scale divisions of the chart. The polarization to TEC conversion tables described in Section 6.7 requires that the phase calibration be 45 divisions. Since all of the AWS-equipped sites have three-channel chart recorders calibrated with 50 divisions full-scale, this should present no problem. The 45-division (generally millimeters), full-deflection span is chosen so that each division represents exactly 4 deg of polarization rotation. The 4-deg reading increment is the desired accuracy of reading, considering the overall polarization errors. These include the satellite-transmitted polarization error, receiving antenna error, non-linearity of the system, etc.

6.2.1 RELATIVE PHASE CALIBRATION

This relative calibration of the polarization channels must be done daily to insure that accurate TEC values are sent to Air Force Global Weather Center (AFGWC). The following procedure should be used:

(1) Use the calibration switch on the front of the polarimeter to alternately switch from one edge of the 45-division calibration to the other edge. Adjust the chart recorder gain and positioning controls for the required deflection. It is desireable to leave the unused 5 divisions of the chart at the top of the chart, so that all readings can be made from the bottom of the chart where the calibration begins. An example of relative phase calibration is shown in Figure 30.

5. Air Weather Service Regulation 105-33, Space Environmental Support System (SESS), Geophysical Sensors Observing Procedures, Dept. of Air Force, Hdqrs AWS(MAC) Scott AFB, Illinois 62225, 14 Feb 1975.

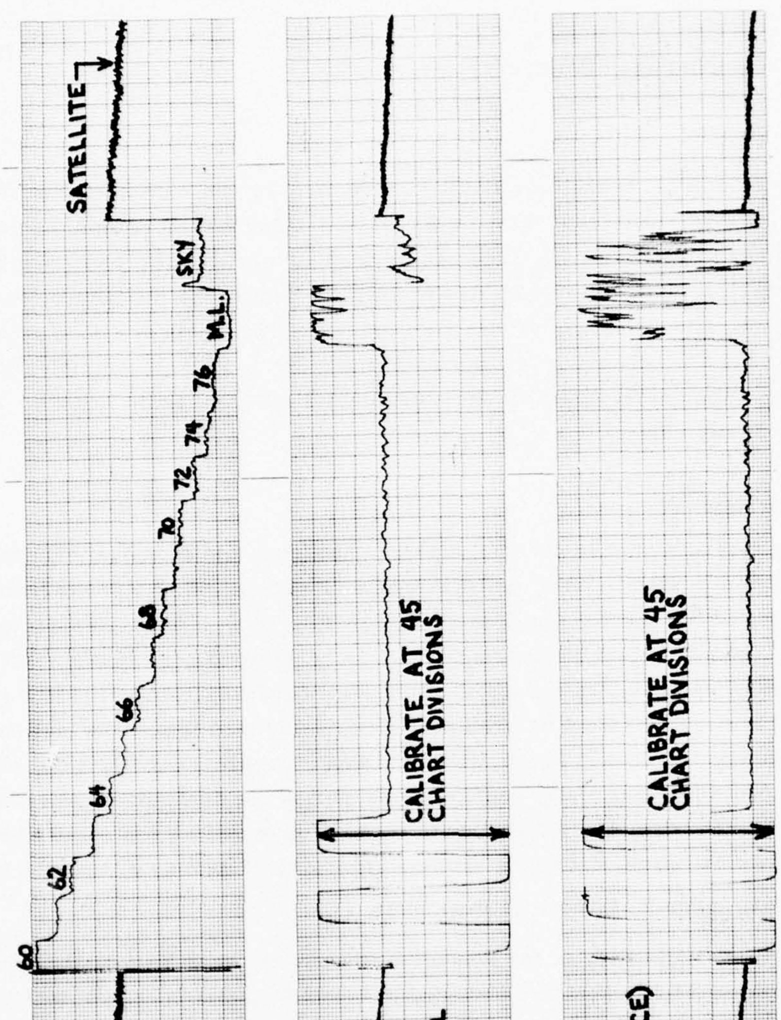

Figure 30. Example of Phase and Amplitude Calibration Chart Record

(2) When making the initial calibration on a newly installed polarimeter, it may be necessary to adjust the gain and position controls inside the polarimeter unit itself if the chart recorder does not have sufficient gain or position offset capability. Refer to the polarimeter instruction manual in the case of the commercially built Aldi unit for further instructions. The AFGL unit has both gain and centering controls located on cards 1 and 2 of the polarimeter adaptor unit which may be adjusted for this purpose if necessary.

(3) After completing the relative calibration of the phase channels, be certain the calibration switch is returned to the operating mode. The AFGL unit is spring loaded and automatically returns to the operating position. However, the Aldi unit must be placed in the "RUN" position.

6.2.2 ABSOLUTE PHASE CALIBRATION

The absolute phase calibration is required so that the chart deflection of an incoming signal of known polarization can be determined. Once this deflection is determined, the chart can be calibrated for any other incoming polarization.

The electronically switched type of polarimeter is particularly well suited for easy calibration of the absolute polarization of the received signal. Since this type of polarimeter uses two orthogonal Yagi antennas, we can easily simulate a signal aligned with one antenna, corresponding to a null on the other antenna, by removing the signal from one antenna and placing a calibration signal approximately equal to the satellite amplitude on the other antenna. This procedure simulates an incoming signal having linear polarization aligned exactly on the antenna input on which the signal is being fed. This calibration is done in the following manner:

(1) First perform the relative phase calibration check, and readjust as necessary to assure that the phase channels have 45 divisions of deflection.

(2) Disconnect both antenna cables from the RF switch inputs. Connect a matched 50 ohm termination to channel "A" and connect the signal generator to input "B" of the RF switch. If the antennas have been connected properly, this procedure simulates an incoming signal having its electric field vector aligned 45 deg counterclockwise with respect to the local vertical when viewing the satellite from behind the antennas.

(3) Retune the receiver as necessary with the signal generator at an output level approximately equal to the satellite signal strength.

(4) The absolute phase calibration can now be read from the reference phase channel in chart divisions (millimeters). Figure 30 shows both an amplitude and an absolute phase calibration. This value should correspond to the reference polarization value listed on the TEC conversion tables furnished monthly to the AWS observers. If these two values do not agree, the instructions on the TEC conversion tables must be followed to correct for this difference. Also, inform AFGWC of the

actual absolute phase calibration so that tables with the correct reference polarization value can be issued in future months.

(5) The absolute phase calibration should be performed whenever the amplitude calibration is done, that is, twice per week.

6.3 Amplitude Calibration

As mentioned earlier, the amplitude channel is very important and its correct calibration, along with an understanding of its usefulness, can be of great use in determining system troubles. In this section we are concerned with its correct calibration for purposes of scaling values of amplitude scintillation during times when ionospheric irregularities are present along the satellite path. The amplitude calibration is performed as follows:

(1) CAUTION—Make calibrations only when the polarization is changing slowly, otherwise data continuity will be lost. To make calibrations, increase the chart recorder speed to 25 mm/min.

(2) If an initial calibration is being made on a new satellite frequency or with a new calibration generator of unknown output level, the signal generator must be first calibrated against the satellite signal level. This is done by tuning in on the satellite signal and adjusting the amplitude channel on the chart recorder for an approximate mid-scale deflection of the satellite signal, with a scale deflection near the bottom edge of the chart when tuned off the satellite signal.

(3) After a mid-scale satellite signal level has been established, disconnect the antenna cables at the inputs to the RF switch and connect the signal generator to input port "B" and a matched load termination to input "A".

(4) Retune the receiver to the signal generator frequency.

(5) Adjust the output level of the signal generator to match the level that the satellite gave in (2) above. Note this level for future reference.

(6) Remove 6 dB of attenuation from the signal generator, thereby increasing the signal by this amount.

(7) Alternately switching the signal generator on and off, adjust the chart recorder gain and position controls for full-scale deflection.

(8) Beginning with the signal at the top of the scale, increase the signal generator attenuation in steps of 1 dB, marking each step in relative numbers that correspond to the signal generator attenuator switch settings. When the 1-dB steps make a difference in chart deflection of less than approximately 2 divisions, use 3-dB steps until a level near the matched load level has been reached.

(9) Turn the signal generator off and mark this chart deflection as the matched termination position.

(10) Reconnect the antenna cables to the RF switch inputs, taking care not to reverse them.

(11) Deliberately tune off the satellite signal far enough so that a chart deflection near the matched load level is recorded. Mark this the "sky" deflection.

(12) Retune to the satellite signal and slowly peak up on the signal by watching the amplitude channel deflection as you tune for a maximum.

(13) Return the chart recorder speed to 1 mm/min.

(14) An example of an amplitude calibration is shown in Figure 30. Note the 1-dB steps in Figure 30, though the handwritten markings of dB levels were done only at 2-dB intervals.

(15) The amplitude calibration must be made twice per week, or more often if you suspect that something has changed in the system gain. By tuning the satellite signal frequency on and off you can easily determine if there is any broadband noise present in the receiver due to a local interference source. The polarimeter may still work satisfactorily with certain types of interference, even though the interference may be considerably stronger than the satellite signal level. The presence of such potentially harmful interference may be easily detected by paying careful attention to the amplitude channel.

6.4 Adding Up the 180 Deg or π Changes to Generate Diurnal TEC Values

As the relative direction of incoming polarization changes, the phase channels that indicate the incoming polarization move through 180 deg of possible deflection on the chart recorder. That is, there is an ambiguity of 180 deg, or π, in the received polarization that the polarimeter does not take into account. There are means of electronically adding up the number of positive and negative changes of 180 deg and representing those changes on an expanded scale having greater range; but, because of susceptibility to interference, these circuits are generally not used in the Air Force operational polarimeter network. Instead, the number of π changes is kept track of manually by the observer. The main reason for having two phase channels is to allow the observer to easily determine the π changes, especially when the polarization is changing in an irregular fashion. An example of irregular polarization change will be shown in Section 6.9.2.

Adding up the π changes is easy. Figure 31 shows a sample chart output for a typical day in October of a solar maximum year. Note how the two chart recorder channels, recorded at the bottom of the figure, are used to reconstruct a complete diurnal curve for that day.

In actual practice no diurnal curve is actually traced by the observer; only the relative π numbers are written on the chart in sequential fashion, as shown on the bottom channel of Figure 31. When polarimeter data are initially reduced, only relative numbers are written on the records. The unknown absolute values of these relative numbers is called $n\pi$ ambiguity. The procedure for determining the $n\pi$

ambiguity is described in Section 6.8. However, it is necessary to first describe the methods of converting Faraday rotation to TEC.

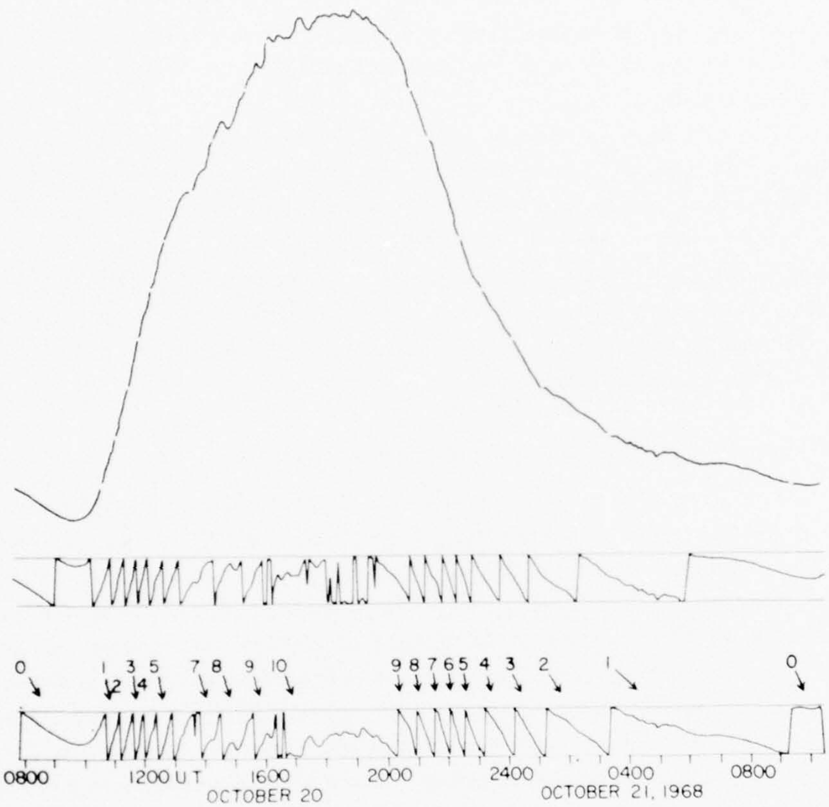

Figure 31. The Polarization Change in a 24-Hour Period for a Typical Day During Solar Maximum. The top trace would be a normal graphic of the change, whereas the bottom two graphs show the actual data trace and how it represents a "folded" version of the top trace. The numbers with arrows indicate the proper π ramp of the folded trace

6.5 Conversion From Faraday Rotation to TEC-Computation

Now that the methods for connecting the VHF polarimeter and performing the relative calibrations of both the amplitude and phase channels have been described, the method for determining the absolute TEC from the chart reading at any time will be explained. In this section the equation that relates observed values of polarization rotation to final TEC values will be described. In a later section the

method for easily making this conversion by using the TEC computer conversion tables will be described. Those observers who use the conversion tables will find that the material in this section is not necessary for the use of those tables; it is, however, useful for background information.

First, the total amount of polarization rotation must be found. For a station in the northern hemisphere the direction to geostationary satellites with respect to the earth's magnetic field is such that an increasing number of electrons produce an increasingly counterclockwise rotation of the plane of polarization of the received signal. Thus, we shall define the counterclockwise direction as the positive rotation direction.

If there were no ionosphere, the received polarization angle in the northern hemisphere would make an angle with respect to the local vertical, as shown in Figure 32:

$$\beta_T - \alpha ,$$

where β_T is the transmitted polarization with respect to the satellite spin axis, and α is the angle the satellite spin axis makes with respect to the local vertical.

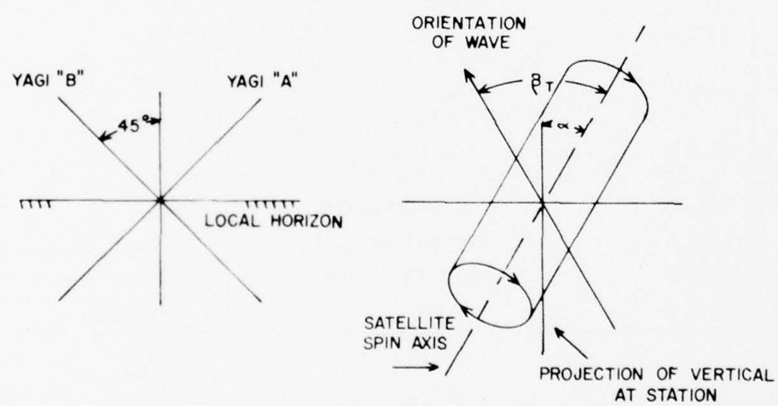

Figure 32. Geometry of Transmitted VHF Signal Polarization With Respect to the Satellite Spin Axis and the Local Horizon

The angle β_T is tabulated for 10 satellites in Table 1; α is given in the table of $\overline{M}$ values for each station looking towards a geostationary satellite at a particular longitude. The angle α can be calculated by the following:[6]

6. Klobuchar, J. A. (1966) Polarization of an az-el mounted antenna viewing celestial objects, IEEE Transactions on Antennas and Propagation, AP-14:(No. 5):650.

$$\sin\alpha = \frac{\cos\phi \sin H}{\sin[\cos^{-1}(\sin\phi \sin\delta + \cos\phi \cos\delta \cos H)]}, \tag{8a}$$

where

H = celestial hour angle of satellite

δ = celestial declination angle of satellite

ϕ = observer's latitude.

Table 1. β_T Values for Various Geostationary Satellites

Satellite Name	f(MHz)	β_T in deg
Syncom 3	136.47 136.98	-40 +40
Early Bird	136.47 136.98	-40 +40
Intelsat 2F2	136.44 136.98	0 0
Intelsat 2F3	136.44 136.98	7 14
Intelsat 2F4	136.44 136.98	-4 ---
ATS 1	136.47 137.35	+30 -33
ATS 3	136.47 137.35	+30 -19
ATS 5	136.47 137.35	+8 -17
ATS 6	40.016 carrier	+90
ATS 6	140.056 carrier	+90
ATS 6	360.144 carrier	-68
SMS 1	136.38	+4

α can also be calculated by an alternate form given by Sengupta:[7]

$$\tan\alpha = \frac{\sin\phi \sin\Delta\theta \sin el \sin az - \cos\Delta\theta \sin el \cos az - \cos\phi \sin\Delta\theta \cos el}{\sin\phi \sin\Delta\theta \cos az + \cos\Delta\theta \sin az} \tag{8b}$$

7. Sengupta, A. (1977) University of Delhi, India, private communication.

where

el = elevation of satellite

az = azimuth of satellite

ϕ = latitude of observer

$\Delta\theta$ = longitude difference between satellite and observer.

Since β_R is the chart reading on the reference channel for a received polarization of 45 deg, β_R-45° is the chart reading for a received vertically polarized signal for antennas mounted as shown in Figure 32. The chart reading at any time is thus given by:

$$\text{CHART READING} = \beta_R - 45° + \beta_T - \alpha + \Omega + n * 180° \,, \qquad (9a)$$

where Ω is the ionospheric Faraday rotation, with an ambiguity of n times 180 deg. At the bottom of the reference channel chart the polarization rotation is:

$$\Omega(o) = \alpha + 45° - \beta_R - \beta_T + n * 180° \,. \qquad (9b)$$

We now know the total polarization rotation at the bottom of the chart channel; we need to calculate the value of TEC that this represents. It is more convenient, however, to calculate the TEC change due to a full-scale or 180 deg change in polarization, since this number is used in determining the $n\pi$ ambiguity. The equation relating TEC to polarization rotation was given in Eq. (7), and for a total rotation change of 1π is:

$$\text{TEC}\ (\pi) = \frac{f^2\ \pi}{2.36 \times 10^{-5}\ \overline{M}} \,, \qquad (10)$$

where $\overline{M}$ is found from the computer tables for geostationary satellites furnished for each station. At this point we assume that the geostationary satellite does not move throughout the day, but remains in a fixed direction so that the $\overline{M}$ does not change with time. As will be seen later in Section 6.7, which describes the polarization to TEC conversion tables, the correction for the movement of the satellite is taken into account in these tables. The correction for the non-stationary position of the satellite can also be taken into account manually by using a different $\overline{M}$ factor in Eq. (10) above, depending upon the exact satellite position; however, this is a more tedious procedure, requiring manual calculations using a different $\overline{M}$ value each time a conversion is made.

When a TEC change corresponding to 180 deg of polarization rotation is known, the absolute value of TEC for the bottom of the reference channel can be found simply by the proportionality:

$$\frac{\Omega(0)}{180} \times \mathrm{TEC}\ (\pi) = \mathrm{TEC}\ (\Omega(0)) \ . \tag{11}$$

6.6 Example of Manual TEC Calculation

First the $\overline{M}$ and the angle α are taken from the computer printout called "Look Angles" for a Geostationary Satellite (Equatorial Orbit) as a function of satellite latitude and longitude. A sample printout for the station at Hamilton, Massachusetts, is shown in Table 2. Note that these tables are for a satellite at stationary height over the equator and are for different longitudes. One need only know the satellite longitude to find the $\overline{M}$ value, α (ALPHA), and the viewing angles to the satellite, elevation, and azimuth. In the example, assume that the signal being received is 136.470 MHz from the satellite ATS-5 which is located at 105 deg West longitude. Further assume that the absolute phase calibration gave a value of 38 millimeters for the chart reading when a known polarization 45 deg counterclockwise to the vertical was received as in the calibration described in Section 6.2.2. From Eq. (10) we have:

$$\mathrm{TEC}\ (\pi) = \frac{1.3647^2 \times 10^{16}\ \pi}{2.36 \times 10^{-5} \times 53,798} = 4.61 \times 10^{16}\ \mathrm{d/m^2} \ .$$

Thus, each 180 deg or π radians of polarization change represents a TEC change of 4.61×10^{16} el/m^2. Also, from Eq. (9b), when the chart reading is at the bottom of the chart channel, we have:

$$\Omega(0) = \alpha + 45^\circ - \beta_R - \beta_T = 31.5 + 45^\circ - 38\ \mathrm{mm} \times \frac{4^\circ}{\mathrm{mm}} - 8^\circ = -83.5^\circ$$

or, adding 180°, 180° - 83.5° = 96.5° .

The bottom of the chart channel, therefore, represents 96.5 deg of rotation, or:

$$\frac{96.5}{180} \times 4.61 \times 10^{16} = 2.47 \times 10^{16}\ \mathrm{el/m^2} \ .$$

When the polarization reading of the reference channel is at the bottom of the chart, the TEC is:

$$[2.47 + N \times 4.61] \times 10^{16}\ \mathrm{el/m^2} \ ,$$

where N can be any integer equal to or greater than zero. However, if the value of N is equal to zero, the minimum TEC value that can be read on the ramp of zero π is, of course, 2.47×10^{16} el/m^2. Since the ionosphere can have fewer electrons than this amount, the N number can go to a value of -1, and the received polarization trace on the reference channel can go as low as a value of 21 mm, which would

correspond to an absolute TEC value of exactly zero. This low a value is extremely unlikely, however, but values lower than 2.5×10^{16} may frequently occur. The ramp labelled -1 is, thus, a normal value for some satellite-station geometries.

Table 2. Look Angles for Geostationary Satellites

LOOK ANGLES FOR A GEOSTATIONARY SATELLITE (EQUATORIAL ORBIT) AS A FUNCTION OF SATELLITE LONGITUDE.(WEST LONG. IS -)

SATELLITE LAT. = 0.000

STATION DATA NAME	LAT	LONG	SUB-IONOSPHERIC HEIGHT
SAG. HILL	42.63	-70.82	420.0

SUBSAT LON	SUB-IONOSPHERIC LAT.	SUB-IONOSPHERIC LONG.	H	PROP ANGLE	SEC Z	G	ELEV	AZIM	RANGE	HOUR ANGLE HR	HOUR ANGLE MIN	HOUR ANGLE SEC	DECLIN DEG	DECLIN MIN	ALPHA
-118.0	39.4	-77.2	-53708.	132.5	1.743	.62	29.3	239.0	403222.	3	10	41	-0	-28.9	38.6
-117.0	39.4	-77.0	-53699.	133.2	1.722	.61	29.9	237.1	403162.	3	6	39	-0	-28.7	38.1
-116.0	39.4	-76.8	-53633.	133.9	1.701	.59	30.6	235.2	403103.	3	2	37	-0	-28.6	37.7
-115.0	39.4	-76.6	-53690.	134.6	1.681	.58	31.2	235.2	403045.	2	58	35	-0	-28.4	37.2
-114.0	39.4	-76.4	-53690.	135.2	1.662	.57	31.8	234.3	402988.	2	54	33	-0	-28.3	36.7
-113.0	39.4	-76.2	-53694.	135.9	1.643	.55	32.4	233.3	402931.	2	50	31	-0	-28.2	36.2
-112.0	39.4	-76.1	-53699.	136.6	1.625	.54	33.0	232.4	402876.	2	45	29	-0	-28.0	35.6
-111.0	39.4	-75.9	-53707.	137.3	1.608	.53	33.6	231.4	402822.	2	42	27	-0	-27.9	35.1
-110.0	39.4	-75.7	-53717.	138.0	1.591	.52	34.1	230.4	402770.	2	38	25	-0	-27.8	34.5
-109.0	39.4	-75.5	-53730.	138.7	1.575	.51	34.7	229.4	402718.	2	34	23	-0	-27.7	33.9
-108.0	39.4	-75.4	-53744.	139.4	1.559	.51	35.3	228.3	402667.	2	30	21	-0	-27.5	33.3
-107.0	39.4	-75.2	-53760.	140.1	1.545	.50	35.8	227.3	402618.	2	26	18	-0	-27.4	32.7
-106.0	39.4	-75.1	-53778.	140.8	1.530	.49	36.4	226.3	402570.	2	22	16	-0	-27.3	32.1
-105.0	39.4	-74.9	-53798.	141.4	1.516	.48	36.9	225.2	402522.	2	18	14	-0	-27.2	31.5
-104.0	39.4	-74.8	-53819.	142.1	1.503	.48	37.4	224.1	402476.	2	14	12	-0	-27.1	30.8
-103.0	39.4	-74.6	-53842.	142.8	1.490	.47	37.9	223.0	402432.	2	10	9	-0	-27.0	30.1
-102.0	39.4	-74.5	-53866.	143.5	1.478	.46	38.4	221.9	402388.	2	6	7	-0	-26.9	29.4
-101.0	39.4	-74.4	-53891.	144.2	1.467	.46	38.9	220.8	402346.	2	2	4	-0	-26.8	28.7
-100.0	39.4	-74.2	-53918.	144.9	1.455	.45	39.4	219.6	402305.	1	58	2	-0	-26.7	28.0
-99.0	39.4	-74.1	-53946.	145.6	1.445	.45	39.9	218.5	402265.	1	54	0	-0	-26.6	27.2
-98.0	39.4	-73.9	-53975.	146.2	1.434	.44	40.3	217.3	402227.	1	49	57	-0	-26.5	26.5
-97.0	39.4	-73.8	-54005.	146.9	1.424	.44	40.8	216.1	402189.	1	45	55	-0	-26.4	25.7
-96.0	39.4	-73.7	-54036.	147.6	1.415	.43	41.2	214.9	402153.	1	41	52	-0	-26.3	24.9
-95.0	39.4	-73.6	-54068.	148.2	1.406	.43	41.6	213.6	402119.	1	37	50	-0	-26.2	24.1
-94.0	39.4	-73.4	-54101.	148.9	1.398	.43	42.1	212.4	402086.	1	33	47	-0	-26.2	23.2
-93.0	39.4	-73.3	-54135.	149.5	1.390	.42	42.4	211.1	402054.	1	29	44	-0	-26.1	22.4
-92.0	39.4	-73.2	-54170.	150.2	1.382	.42	42.8	209.9	402023.	1	25	42	-0	-26.0	21.5
-91.0	39.4	-73.1	-54206.	150.8	1.375	.42	43.2	208.6	401994.	1	21	39	-0	-25.9	20.6
-90.0	39.4	-73.0	-54243.	151.4	1.368	.41	43.5	207.3	401966.	1	17	37	-0	-25.9	19.7
-89.0	39.4	-72.8	-54280.	152.0	1.361	.41	43.9	206.0	401939.	1	13	34	-0	-25.8	18.8
-88.0	39.4	-72.7	-54318.	152.6	1.355	.41	44.2	204.6	401914.	1	9	31	-0	-25.7	17.9
-87.0	39.4	-72.6	-54358.	153.2	1.349	.41	44.5	203.3	401890.	1	5	29	-0	-25.7	16.9
-86.0	39.4	-72.5	-54398.	153.8	1.344	.41	44.8	201.9	401868.	1	1	26	-0	-25.6	15.9
-85.0	39.4	-72.4	-54439.	154.4	1.339	.40	45.0	200.5	401847.	0	57	23	-0	-25.6	15.0
-84.0	39.4	-72.3	-54480.	154.9	1.335	.40	45.3	199.1	401827.	0	53	20	-0	-25.5	14.0
-83.0	39.4	-72.1	-54523.	155.5	1.330	.40	45.5	197.7	401809.	0	49	18	-0	-25.5	13.0
-82.0	39.4	-72.0	-54566.	156.0	1.326	.40	45.8	196.3	401792.	0	45	15	-0	-25.5	11.9
-81.0	39.4	-71.9	-54610.	156.5	1.323	.40	46.0	194.9	401777.	0	41	12	-0	-25.4	10.9
-80.0	39.4	-71.8	-54655.	156.9	1.320	.40	46.1	193.5	401763.	0	37	10	-0	-25.4	9.9
-79.0	39.4	-71.7	-54700.	157.4	1.317	.40	46.3	192.0	401750.	0	33	7	-0	-25.4	8.8
-78.0	39.4	-71.6	-54747.	157.8	1.314	.40	46.5	190.6	401739.	0	29	4	-0	-25.3	7.8
-77.0	39.4	-71.5	-54794.	158.2	1.312	.40	46.6	189.1	401729.	0	25	1	-0	-25.3	6.7
-76.0	39.4	-71.4	-54842.	158.6	1.310	.40	46.7	187.7	401721.	0	20	58	-0	-25.3	5.6
-75.0	39.4	-71.3	-54891.	158.9	1.309	.40	46.8	186.2	401714.	0	16	56	-0	-25.3	4.5
-74.0	39.4	-71.2	-54940.	159.3	1.307	.40	46.9	184.7	401709.	0	12	53	-0	-25.3	3.5
-73.0	39.4	-71.1	-54991.	159.6	1.306	.40	46.9	183.2	401705.	0	8	50	-0	-25.2	2.4
-72.0	39.4	-70.9	-55042.	159.8	1.306	.41	46.9	181.8	401703.	0	4	47	-0	-25.2	1.3
-71.0	39.4	-70.8	-55094.	160.0	1.306	.41	46.9	180.3	401702.	0	0	44	-0	-25.2	.2
-70.0	39.4	-70.7	-55148.	160.2	1.306	.41	46.9	178.8	401702.	23	56	42	-0	-25.2	-.9
-69.0	39.4	-70.6	-55202.	160.4	1.306	.41	46.9	177.3	401704.	23	52	39	-0	-25.2	-2.0
-68.0	39.4	-70.5	-55257.	160.5	1.307	.41	46.9	175.8	401707.	23	48	36	-0	-25.3	-3.1
-67.0	39.4	-70.4	-55313.	160.6	1.308	.42	46.8	174.4	401712.	23	44	33	-0	-25.3	-4.1
-66.0	39.4	-70.3	-55370.	160.6	1.309	.42	46.7	172.9	401718.	23	40	30	-0	-25.3	-5.2
-65.0	39.4	-70.2	-55428.	160.6	1.311	.42	46.6	171.4	401726.	23	36	28	-0	-25.3	-6.3
-64.0	39.4	-70.1	-55487.	160.6	1.313	.43	46.5	170.0	401735.	23	32	25	-0	-25.3	-7.4
-63.0	39.4	-70.0	-55547.	160.5	1.316	.43	46.4	168.5	401746.	23	28	22	-0	-25.3	-8.4
-62.0	39.4	-69.9	-55608.	160.4	1.318	.43	46.2	167.1	401758.	23	24	19	-0	-25.4	-9.5
-61.0	39.4	-69.7	-55670.	160.3	1.322	.44	46.0	165.6	401771.	23	20	17	-0	-25.4	-10.5
-60.0	39.4	-69.6	-55734.	160.1	1.325	.44	45.8	164.2	401786.	23	16	14	-0	-25.4	-11.6
-59.0	39.4	-69.5	-55799.	159.9	1.329	.45	45.6	162.8	401802.	23	12	11	-0	-25.5	-12.6
-58.0	39.4	-69.4	-55865.	159.6	1.333	.45	45.4	161.4	401820.	23	8	8	-0	-25.5	-13.6
-57.0	39.4	-69.3	-55932.	159.4	1.337	.46	45.1	160.0	401839.	23	4	6	-0	-25.6	-14.6
-56.0	39.4	-69.2	-56001.	159.1	1.342	.46	44.9	158.6	401860.	23	0	3	-0	-25.6	-15.6
-55.0	39.4	-69.1	-56071.	158.7	1.347	.47	44.6	157.2	401882.	22	56	0	-0	-25.7	-16.5
-54.0	39.4	-69.0	-56142.	158.4	1.353	.47	44.3	155.9	401905.	22	51	57	-0	-25.7	-17.5
-53.0	39.4	-68.8	-56215.	158.0	1.359	.48	44.0	154.5	401930.	22	47	55	-0	-25.8	-18.4

The final relationship between values of N number and reference channel deflection in millimeters and the resulting TEC value is then:

$$TEC = [2.47 + N \times 4.61 + \frac{\text{CHART READING}^{(\text{in mm})}}{45} \times 4.61] \times 10^{16}\ el/m^2 ,$$

where the value of N can be any integer equal to or greater than -1.

The final question that requires an answer before we can read the absolute TEC value is: What is the value of N? This question is called the N ambiguity and is discussed in Section 6.8. First the use of conversion tables furnished to all AWS observers is discussed. The conversion tables automatically take into account all the calculations detailed in this section, thereby making the AWS observer's task merely one of keeping track of the value of N and reading the chart reference channel deflection in millimeters.

6.7 Conversion From Faraday Rotation to TEC-Use of Conversion Tables

Satellites placed into geostationary orbits do not stay in precisely the same location, they move through a small angular arc on a diurnal basis due to the non-zero inclination of the orbital plane to the earth's orbital plane; therefore, the assumption of a constant $\overline{M}$ factor for the conversion of observed polarization rotation values to TEC is incorrect. For some of the older satellites, the inclination is over 6 deg and the diurnal changes in the $\overline{M}$ factor due to the drift can reach plus and minus 20 percent, hardly a constant. To obtain the best possible TEC value from the observations, conversion tables have been made up for use in converting the values of polarization read off the raw data in chart divisions to final TEC values. The use of these tables is straightforward and much easier than performing the calculations described in the previous section.

With this TEC reduction method, the chart polarization channels are ALWAYS calibrated for 45 divisions full-scale deflection using the calibration switch, regardless of the station or satellite being monitored. Mark the absolute N π numbers according to the method described in Section 6.8. Read the chart deflection up from the bottom of the calibration to the chart trace in units of chart divisions (millimeters). Now, with these two numbers for the time of the observation, simply look up the final TEC value in the conversion tables for that pair of values for the correct hour of the observation. Table 3 is a sample page of the conversion table for Goose Bay, Labrador, for use in April 1976 for the satellite ATS-3 on 136.470 MHz.

Table 3. Faraday to TEC Conversion Table

DATE	STATION	SATELLITE	(NOMINAL LONGITUDE)	FREQUENCY (MHZ)	REFERENCE POLARIZATION VALUE (MM)
APRIL 1976	GOOSE BAY	ATS3	-68.7	136.470	18.0

CHART READINGS		TIME(U.T.)																							
PI	MM	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
3	0	11.7	11.7	11.7	11.6	11.5	11.4	11.3	11.1	10.9	10.8	10.6	10.5	10.4	10.4	10.4	10.5	10.6	10.8	10.9	11.1	11.3	11.4	11.6	11.7
3	1	11.8	11.8	11.8	11.7	11.6	11.5	11.4	11.2	11.0	10.9	10.7	10.5	10.5	10.5	10.5	10.6	10.7	10.8	11.0	11.2	11.4	11.5	11.7	11.7
3	2	11.9	11.9	11.9	11.8	11.7	11.6	11.5	11.3	11.1	10.9	10.8	10.7	10.6	10.6	10.6	10.7	10.8	10.9	11.1	11.3	11.5	11.6	11.7	11.8
3	3	12.0	12.0	12.0	11.9	11.8	11.7	11.5	11.4	11.2	11.0	10.9	10.8	10.7	10.7	10.7	10.8	10.9	11.0	11.2	11.4	11.6	11.7	11.8	11.9
3	4	12.1	12.1	12.1	12.0	11.9	11.8	11.6	11.5	11.3	11.1	11.0	10.8	10.8	10.7	10.8	10.8	11.0	11.1	11.3	11.5	11.6	11.8	11.9	12.0
3	5	12.2	12.2	12.2	12.1	12.0	11.9	11.7	11.6	11.4	11.2	11.1	10.9	10.9	10.8	10.9	10.9	11.0	11.2	11.4	11.6	11.7	11.9	12.0	12.1
3	6	12.3	12.3	12.3	12.2	12.1	12.0	11.8	11.6	11.5	11.3	11.1	11.0	10.9	10.9	10.9	11.0	11.1	11.3	11.5	11.6	11.8	12.0	12.1	12.2
3	7	12.4	12.4	12.4	12.3	12.2	12.1	11.9	11.7	11.6	11.4	11.2	11.1	11.0	11.0	11.0	11.1	11.2	11.4	11.6	11.7	11.9	12.1	12.2	12.3
3	8	12.5	12.5	12.5	12.4	12.3	12.2	12.0	11.8	11.6	11.5	11.3	11.2	11.1	11.1	11.1	11.2	11.3	11.5	11.6	11.8	12.0	12.2	12.3	12.4
3	9	12.6	12.6	12.6	12.5	12.4	12.3	12.1	11.9	11.7	11.6	11.4	11.3	11.2	11.2	11.2	11.3	11.4	11.5	11.7	11.9	12.1	12.3	12.4	12.5
3	10	12.7	12.7	12.7	12.6	12.5	12.4	12.2	12.0	11.8	11.6	11.5	11.4	11.3	11.3	11.3	11.4	11.5	11.6	11.8	12.0	12.2	12.4	12.5	12.6
3	11	12.8	12.8	12.8	12.7	12.6	12.4	12.3	12.1	11.9	11.7	11.6	11.5	11.4	11.3	11.4	11.4	11.6	11.7	11.9	12.1	12.3	12.5	12.6	12.7
3	12	12.9	12.9	12.8	12.8	12.7	12.5	12.4	12.2	12.0	11.8	11.7	11.6	11.5	11.4	11.4	11.5	11.7	11.8	12.0	12.2	12.4	12.6	12.7	12.8
3	13	13.0	13.0	12.9	12.9	12.8	12.6	12.5	12.3	12.1	11.9	11.8	11.6	11.5	11.5	11.5	11.6	11.7	11.9	12.1	12.3	12.5	12.6	12.8	12.9
3	14	13.0	13.1	13.0	13.0	12.9	12.7	12.6	12.4	12.2	12.0	11.8	11.7	11.6	11.6	11.6	11.7	11.8	12.0	12.2	12.4	12.6	12.7	12.9	13.0
3	15	13.1	13.2	13.1	13.1	13.0	12.8	12.6	12.5	12.3	12.1	11.9	11.9	11.7	11.7	11.7	11.8	11.9	12.1	12.3	12.5	12.7	12.8	13.0	13.1
3	16	13.2	13.3	13.2	13.2	13.1	12.9	12.7	12.6	12.4	12.2	12.0	11.9	11.8	11.8	11.8	11.9	12.0	12.2	12.4	12.6	12.8	12.9	13.1	13.2
3	17	13.3	13.4	13.3	13.3	13.1	13.0	12.8	12.6	12.5	12.3	12.1	12.0	11.9	11.8	11.9	12.0	12.1	12.3	12.4	12.6	12.8	13.0	13.2	13.3
3	18	13.4	13.4	13.4	13.4	13.2	13.1	12.9	12.7	12.5	12.4	12.2	12.1	12.0	11.9	12.0	12.0	12.2	12.3	12.5	12.7	12.9	13.1	13.3	13.4
3	19	13.5	13.5	13.5	13.4	13.3	13.2	13.0	12.8	12.6	12.4	12.3	12.1	12.1	12.0	12.0	12.1	12.3	12.4	12.6	12.8	13.0	13.2	13.4	13.5
3	20	13.6	13.6	13.6	13.5	13.4	13.3	13.1	12.9	12.7	12.5	12.4	12.2	12.1	12.1	12.1	12.2	12.3	12.5	12.7	12.9	13.1	13.3	13.4	13.6
3	21	13.7	13.7	13.7	13.6	13.5	13.4	13.2	13.0	12.8	12.6	12.4	12.3	12.2	12.2	12.2	12.3	12.4	12.6	12.8	13.0	13.2	13.4	13.5	13.7
3	22	13.8	13.8	13.8	13.7	13.6	13.5	13.3	13.1	12.9	12.7	12.5	12.4	12.3	12.3	12.3	12.4	12.5	12.7	12.9	13.1	13.3	13.5	13.6	13.7
3	23	13.9	13.9	13.9	13.8	13.7	13.6	13.4	13.2	13.0	12.8	12.6	12.5	12.4	12.4	12.4	12.5	12.6	12.8	13.0	13.2	13.4	13.6	13.7	13.8
3	24	14.0	14.0	14.0	13.9	13.8	13.7	13.5	13.3	13.1	12.9	12.7	12.5	12.5	12.4	12.5	12.6	12.7	12.9	13.1	13.3	13.5	13.7	13.8	13.9
3	25	14.1	14.1	14.1	14.0	13.9	13.8	13.6	13.4	13.2	13.0	12.8	12.7	12.6	12.5	12.6	12.6	12.8	13.0	13.2	13.4	13.6	13.8	13.9	14.0
3	26	14.2	14.2	14.2	14.1	14.0	13.8	13.7	13.5	13.3	13.1	12.9	12.7	12.6	12.6	12.6	12.7	12.9	13.0	13.2	13.5	13.7	13.9	14.0	14.1
3	27	14.3	14.3	14.3	14.2	14.1	13.9	13.8	13.6	13.3	13.1	13.0	12.8	12.7	12.7	12.7	12.8	13.0	13.1	13.3	13.6	13.8	14.0	14.1	14.2
3	28	14.4	14.4	14.4	14.3	14.2	14.0	13.8	13.6	13.4	13.2	13.1	12.9	12.8	12.8	12.8	12.9	13.0	13.2	13.4	13.6	13.9	14.0	14.2	14.3
3	29	14.5	14.5	14.5	14.4	14.3	14.1	13.9	13.7	13.5	13.3	13.1	13.0	12.9	12.9	12.9	13.0	13.1	13.3	13.5	13.7	13.9	14.1	14.3	14.4
3	30	14.6	14.6	14.6	14.5	14.4	14.2	14.0	13.8	13.6	13.4	13.2	13.1	13.0	13.0	13.0	13.1	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.5
3	31	14.7	14.7	14.7	14.6	14.5	14.3	14.1	13.9	13.7	13.5	13.3	13.2	13.1	13.0	13.1	13.2	13.3	13.5	13.7	13.9	14.1	14.3	14.5	14.6
3	32	14.8	14.8	14.8	14.7	14.6	14.4	14.2	14.0	13.8	13.6	13.4	13.3	13.2	13.1	13.2	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.7
3	33	14.9	14.9	14.9	14.8	14.7	14.5	14.3	14.1	13.9	13.7	13.5	13.3	13.2	13.2	13.2	13.3	13.5	13.7	13.9	14.1	14.3	14.5	14.7	14.8
3	34	15.0	15.0	15.0	14.9	14.8	14.6	14.4	14.2	14.0	13.8	13.6	13.4	13.3	13.3	13.3	13.4	13.6	13.7	14.0	14.2	14.4	14.6	14.8	14.9
3	35	15.1	15.1	15.0	15.0	14.8	14.7	14.5	14.3	14.1	13.8	13.7	13.5	13.4	13.4	13.4	13.5	13.6	13.8	14.1	14.3	14.5	14.7	14.9	15.0
3	36	15.1	15.2	15.1	15.1	14.9	14.8	14.6	14.4	14.1	13.9	13.7	13.5	13.5	13.5	13.5	13.6	13.7	13.9	14.1	14.4	14.6	14.8	15.0	15.1
3	37	15.2	15.3	15.2	15.2	15.0	14.9	14.7	14.5	14.2	14.0	13.8	13.7	13.6	13.5	13.6	13.7	13.8	14.0	14.2	14.5	14.7	14.9	15.1	15.2
3	38	15.3	15.4	15.3	15.3	15.1	15.0	14.8	14.6	14.3	14.1	13.9	13.8	13.7	13.6	13.7	13.8	13.9	14.1	14.3	14.6	14.8	15.0	15.1	15.3
3	39	15.4	15.5	15.4	15.4	15.2	15.1	14.9	14.6	14.4	14.2	14.0	13.9	13.8	13.7	13.7	13.8	14.0	14.2	14.4	14.6	14.9	15.1	15.2	15.4
3	40	15.5	15.6	15.5	15.4	15.3	15.2	15.0	14.7	14.5	14.3	14.1	13.9	13.8	13.8	13.8	13.9	14.1	14.3	14.5	14.7	15.0	15.2	15.3	15.5
3	41	15.6	15.7	15.6	15.5	15.4	15.2	15.0	14.8	14.6	14.4	14.2	14.0	13.9	13.9	13.9	14.0	14.2	14.4	14.6	14.8	15.1	15.3	15.4	15.6
3	42	15.7	15.7	15.7	15.6	15.5	15.3	15.1	14.9	14.7	14.5	14.3	14.1	14.0	14.0	14.0	14.1	14.3	14.5	14.7	14.9	15.1	15.4	15.5	15.7
3	43	15.8	15.8	15.8	15.7	15.6	15.4	15.2	15.0	14.8	14.6	14.4	14.2	14.1	14.1	14.1	14.2	14.3	14.5	14.8	15.0	15.2	15.4	15.6	15.7
3	44	15.9	15.9	15.9	15.8	15.7	15.5	15.3	15.1	14.9	14.6	14.4	14.3	14.2	14.1	14.2	14.3	14.4	14.6	14.9	15.1	15.3	15.5	15.7	15.8

If your observation falls exactly on the hour, you may read the final TEC value directly. If your observation is at 15, 30, or 45 min past the hour, you should interpolate between the two hourly values given in the conversion tables for that particular π number and number of divisions of chart deflection. For example, the Goose Bay Station for the month, satellite, receiving frequency, and reference polarization value listed in Table 3 has an observed polarization value of 23 divisions on the 3π ramp at 1730 UT. From Table 3 the final TEC value is 12.9 TEC units. It is important to use the proper conversion tables for the satellite, the station, the frequency, and the reference polarization.

Remember that the polarization channel deflection of 45 mm is to be adjusted using the calibration switch. The actual deflection of the channels when receiving a satellite signal of changing polarization will generally not exceed 43 mm or go below approximately 2 mm. This is due to the less than ideal signal-to-noise ratio and is characteristic of all polarimeters operating at the same signal-to-noise ratio. When the reference channel indicates a value within the "dead zone", or the region where polarization is switching back between ramps, the chart reading may easily be taken on the orthogonal polarization channel, which will be near the middle of its ramp. Be certain to either add or subtract one half the full-scale deflection, that is, 22.5 mm, from the reading taken on the orthogonal channel to give an equivalent reading that would have been taken on the reference channel.

6.8 Determination of the $n\pi$ Ambiguity

The determination of the absolute total amount of polarization rotation of the signal transmitted from a geostationary satellite platform and received by a VHF electronic polarimeter requires knowing how many times 180 deg of rotation has occurred between the satellite and the receiver. Thus far we have discussed how to determine the amount of rotation at the bottom of the reference channel and how to calculate the relative electron content change for a full-scale change of 180 deg of chart deflection. It remains for us to determine how many additional 180 deg or $n\pi$ changes have occurred at any time so that the final TEC value can be determined.

First of all, remember that continuity of data is very important. If there are no equipment failures or satellite transmitter outages, a continuous recording of many days, weeks, or months without losing track of the relative $n\pi$ value is possible and can be achieved in practice. Therefore, if only one $n\pi$ value can be unambiguously determined, all others are then known simply by counting up and down as the values change throughout each day.

Since the single-frequency Faraday measurement at VHF is not an inherently absolute measure of TEC, but only of changes in this parameter, some other method of determining the $n\pi$ value at a particular time must be used. The method recommended here is to utilize a measurement of the density at the peak of the F_2 region

called N_{max}, obtained from an ionosonde value of foF2, and determine a TEC value from reasonable values of the ratio of TEC divided by N_{max} at a time when the chances for error in this procedure are minimized. Since both TEC and N_{max} are generally lowest at most locations during the late nighttime hours, this is the time chosen to determine the $n\pi$ ambiguity.

It is best to obtain an N_{max} or foF2 value from an ionosonde located at the point where the radio wave from the satellite intersects the ionosphere at a height of approximately 300 to 400 km, that is, somewhat equatorward of the station location and within plus or minus 15 deg of the station longitude. Hopefully there will be an ionosonde located somewhat near the TEC measurement station from which hourly values of foF2 can be obtained. AWS observers may obtain values of foF2 from the AWS Automated Data Network (ADN). See Figure 33. The foF2 values are transmitted on the ADN in a coded form with a heading of: UFOFH. The code breakdown, reproduced from the International URSIgram Synoptic Code Manual,[8] is shown in Figure 34.

After obtaining an foF2 value for a late nighttime hour (not too close to sunrise), enter the Nomograph given in Figure 35 with the foF2 value and the various reasonable possibilities for TEC that you have calculated from the polarization reading. With a straight edge, find the TEC value that most nearly corresponds to a slab-thickness value of between 200 and 300 km; this TEC value corresponds to the appropriate $n\pi$ value.

```
NNNN
KBOU
HXUS BOU 221510
UFOFH 17402 61021 /1300 30356 40569 5060/ 60656 70619 80726
90736 00706 10690 20730 3066/ 0057/ 10426 20386 3035/ 4031/
50344 60366 70306 80006 90006 00006 10306 20290
BT
```

Figure 33. Example of Teletype Message From Wallops Island. The code breakdown is as shown in Figure 34

8. Synoptic Codes for Solar and Geophysical Data, published by the International URSIgram and World Days Services, IUWDS. Copies available from Deputy Secretary for URSIgrams, IUWDS, SEL/ERL/NOAA, Boulder, Colorado 80302.

PART F.I.1

UFOFO or UFOFD or UMUFD

1. Content.

- Critical frequencies of F2 region (foF2) as a function of time
- Maximum and minimum values of foF2 and hour of occurrence
- *f-min frequencies for every six hours (first hours same as for* first foF2 group)

2. General form.

UFOFO or UFOFD or UMUFD   IIIII   YMMDD   /HHmm   fgggh   fgggh   fgggh   fgggh   MAXMI   HHpp

- HHpp — time of maximum and maximum value of foF2
- MAXMI — key word
- fgggh — hour indicator, value of foF2 and descriptive symbol
- /HHmm — filler/and UT hour and minute of start of 24-hour period
- YMMDD — last digit of year, month and UT date
- IIIII — station indicator
- UFOFO or UFOFD or UMUFD — key word

HHqqq   EFMIN   iijjk   kllXX

- kllXX — value of f-min or descriptive symbol
- iijjk — value of f-min or descriptive symbol
- EFMIN — key word
- HHqqq — time of minimum and minimum value of foF2

3. Definition of symbols.

UFOFO = key word, foF2, code 0 (every six hours, Universal time)

UFOFD = key word, foF2, code D (every hour, Universal time)

UMUFD = key word, Maximum Usable Frequency Factor (3000) F2, code D (every hour, Universal time)

IIIII = station indicator (See lists in Part A.V)

Y = last digit of year
MM = two digits to represent month of year
DD = two digits to represent UT day of month

/ = filler
HHmm = *UT hour and minute of beginning of period*

f = even hour indicator (for UFOFO), give data for 0000, 0600, 1200, and 1800, beginning with the appropriate hour after the date
0 = 0000 hours   6 = 1200
3 = 0600   9 = 1800

Notes: 1. UFOFD is the same as UFOFU and UFOFO except values will be given for every hour, Universal time. The definition of "f" for this code is extended as follows:

0 = 0000	6 = 0600	2 = 1200	8 = 1800
1 = 0100	7 = 0700	3 = 1300	9 = 1900
2 = 0200	8 = 0800	4 = 1400	0 = 2000
3 = 0300	9 = 0900	5 = 1500	1 = 2100
4 = 0400	0 = 1000	6 = 1600	2 = 2200
5 = 0500	1 = 1100	7 = 1700	3 = 2300

2. For UMUFD the definition of "f" is as given in Note 1.

ggg = value of foF2 (in tenths of MHz; report as 000 if symbols only are applicable) or value of M(3000)F2 in hundredths

h = descriptive letter symbol (see Piggott and Rawer, URSI Handbook of Ionogram Interpretation and Reduction, 1961, for full information)

X = none (use slant line in teletype messages)
1 = A, blanketing sporadic E
2 = B, complete absorption
3 = C, equipment trouble
4 = D, frequency higher than equipment limit
5 = E, frequency lower than equipment limit
6 = F, spread echoes
7 = G, foF2 $\leq$ foF1 (report foF1 in group "ggg" above)
8 = I or T, interpolated or smoothed value
9 = R, measurement influenced by, or impossible because of attenuation in the vicinity of a critical frequency
0 = any other

Figure 34. URSIgram Synoptic Cable Breakdown

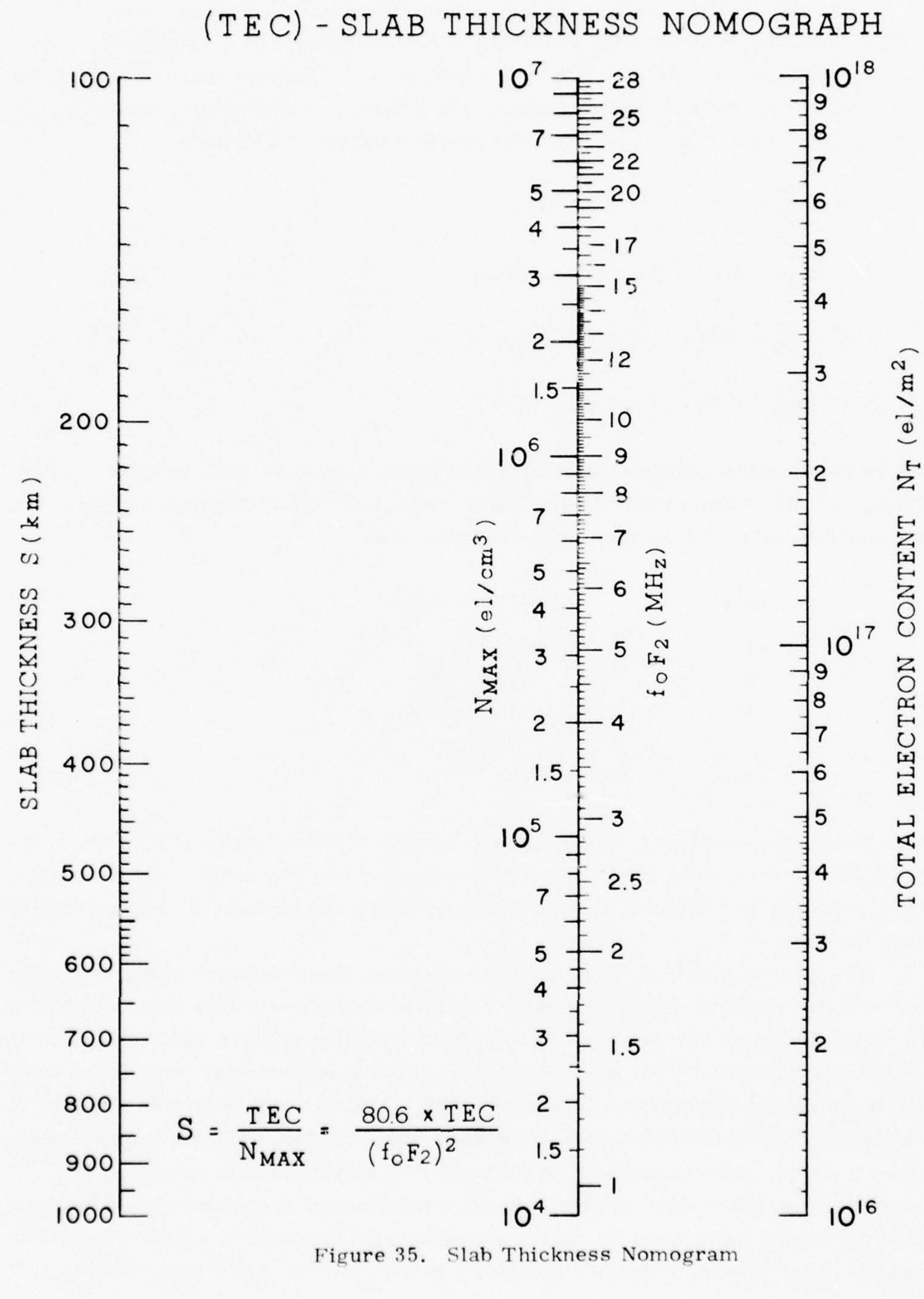

Figure 35. Slab Thickness Nomogram

From the example given in Section 6.6 for the Hamilton station monitoring ATS-5, we know the following: When the reference polarization channel is at the bottom, the TEC is 2.47×10^{16} plus $N \times 4.61 \times 10^{16}$. Suppose that at the time the foF2 value is given (well before sunrise) the reference polarization channel is reading 33 mm of deflection. Then the possible values of TEC are:

$$2.47 + \frac{33}{45} \times 4.61 - 1 \times 4.61 = 1.2$$

$$2.47 + \frac{33}{45} \times 4.61 + 0 \times 4.61 = 5.8$$

$$2.47 + \frac{33}{45} \times 4.61 + 1 \times 4.61 = 10.4$$

$$2.47 + \frac{33}{45} \times 4.61 + 2 \times 4.61 = 15.0 \,,$$

where the smallest possible value of N that yields a positive TEC value is, in this case, -1. The value of foF2 is 4.4 MHz. Now, from the nomograph in Figure 35, the possible values of the ratio slab thickness are:

N number	Slab Thickness
-1	<<100 km
0	240 km
1	435 km
2	620 km
etc.	

From our criterion of a reasonable thickness of the ionospheric F2 region, we must choose the n value equal to 0 for this time period. Generally, determining the $n\pi$ number is simple during the nighttime hours and during and near solar minimum periods.

It is generally helpful if values of foF2 for two or more hours are used, along with relative TEC values for the same hours, to determine values of slab thickness. In using this procedure be sure to use periods when the relative TEC values are low and nearly constant. That is, stay away from the dawn period or from times when the polarization records are changing rapidly. After $n\pi$ ambiguity and absolute TEC calibration procedures have been completed, the final TEC values can be obtained from the reference channel without difficulty. If slab-thickness values of, for example, say 350 km are obtained, the $n\pi$ determination procedure should be used every day until the ambiguous values are resolved. Otherwise, $n\pi$ determinations need only be repeated when data continuity is lost or as a "make sure" check.

During periods of little TEC change, "make sure" checks should be performed at least once a week.

6.9 Examples of Types of TEC Events

In this section examples of changes in received polarization angle during unusual solar or geomagnetic activity are shown. The observer is cautioned to study the accompanying figures carefully to better be able to discern these types of changes on records taken at his station. Whenever geomagnetic activity is predicted or is in progress, the chart-recorder speed should be increased from the normal 1 mm/min to 5 mm/min, or even faster if the speed of the polarization changes warrants it, such as at high-latitude locations where the polarization changes can be extremely rapid and irregular.

6.9.1 SITEC - A SUDDEN INCREASE IN TEC DURING A SOLAR FLARE

A sudden increase in TEC (SITEC) often occurs during large solar flares, see Figure 36. The SITEC is due to the marked increase in the electron content of the lower ionosphere caused by the increase in solar EUV and X-ray radiation. The TEC curve roughly follows the X-ray flux with a rapid increase followed by a gradual decrease. The post-event TEC value may remain above the normal diurnal pattern for some time, perhaps for several hours. Note how the increase occurred within a time period of less than 1 min and remained above the pre-flare level for a long period, gradually becoming lost in the normal diurnal TEC change. Since SITECs generally occur without advance warning, the chart-recorder speed cannot be increased to increase the resolution of the trace. However, once a SITEC is observed, a geomagnetic disturbance generally follows within a day or so. Thus, when a SITEC occurs it is generally wise to increase the chart paper speed to 5 mm/min for the next 2 days to be certain of recording the rapid changes in TEC that may occur.

6.9.2 TEC OBSERVATIONS DURING GEOMAGNETIC STORMS

Dramatic changes in TEC from the monthly average behavior sometimes occur during magnetic storms. It is the purpose of this short section to acquaint the observer with the types of changes that might occur in received polarization angle during these periods, and to urge him to pay close attention to the recordings during these periods and to report these unusual TEC values with confidence to AFGWC.

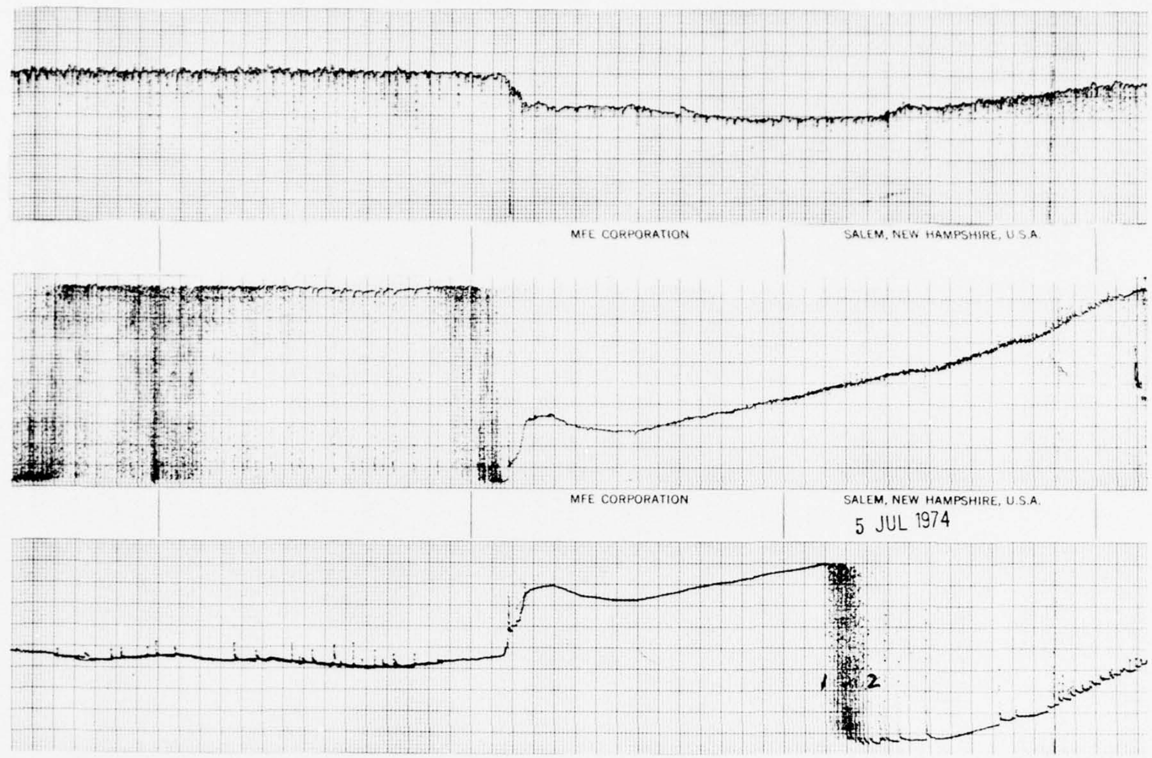

Figure 36. A SITEC is Shown at the Center of the Data Record

If the magnetic storm is large and if the storm commencement time occurs within the proper time interval, mid-latitude stations may observe a large, rapid increase in polarization in mid-afternoon that can give a TEC value of more than two to three times the normal afternoon maximum value. If this large maximum occurs, it generally will be followed by a very rapid drop in TEC, generally back to or below the normal value within a one-half hour period or less. This rapid drop will occur near dusk.

The polarimeter is capable of following changes at rates of up to 1 π every few seconds, but the chart recorder must be run at a fast enough speed to record the rapid drop in TEC. The fastest change in polarization ever seen was approximately 1 π per 30 sec; thus, at the 5 mm/min speed, no difficulty will be experienced in seeing this rapid change. Figure 37 shows an example of a rapid drop in TEC observed during a geomagnetic storm, at 2200 UT on 1 November 1968. The 28 October trace on the top portion of Figure 37 shows a more typical TEC change with time.

During the nighttime period at the mid- and high-latitude stations, the disturbed auroral region moves southward and the polarization changes observed through this disturbed auroral precipitation region are very irregular and quite rapid. Even with these rapid, irregular changes, it is possible to properly monitor the polarization changes if the chart recorder is running at 5 mm/min. During these times the TEC data sent to AFGWC should be sent along with a qualifier to the effect that the TEC is very irregular. Figure 38 shows an example of polarization changes recorded at Goose Bay, Labrador, while auroral precipitation was occurring along the ray path from the satellite to the station. Notice the rapid, irregular changes in observed polarization angle. During these periods extremely heavy, rapid, amplitude scintillations generally occur, as illustrated in Figure 38. Figure 37 also shows rapid, irregular polarization changes after the rapid drop in TEC on 1 November 1968.

6.9.3 SOLAR NOISE STORM INTERFERENCE

The sun can produce large amounts of VHF radio noise during solar noise storms. This interference decreases the satellite signal's signal-to-noise ratio. Very large storms can cause a loss of satellite signal, when the solar noise masks the satellite signal as shown in Figure 39.

Solar noise storms can last for hours or days and can severely degrade the polarimeter output ramp quality. When the sun is in the rather large beamwidth of the Yagi Antennas, as seen in Figure 39 from after 1500 to 1800 UT, the ramps can be severely compressed due to the poor signal-to-noise ratio. During these times no useful data can be taken, but hopefully, the number of π changes that occur can at least be counted. Sometimes this is not even possible, and the absolute π number must be determined again. Fortunately, large solar noise storms are fairly rare occurrences.

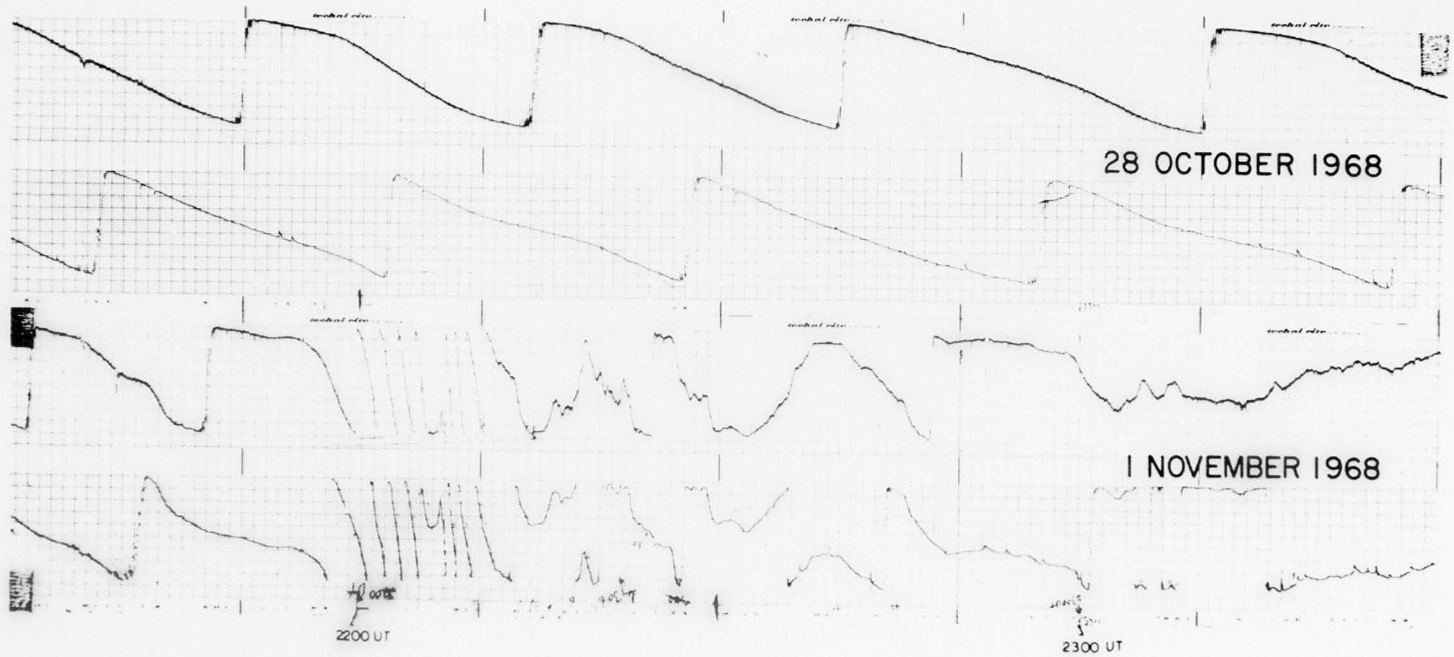

Figure 37. Total Electron Content From AFGL Polarimeter. Onset of visible aurora at 2200 UT on 1 November; 28 October was a quiet day. Note that the AFGL polarimeter readily follows fast changes. Time constant = 1 sec

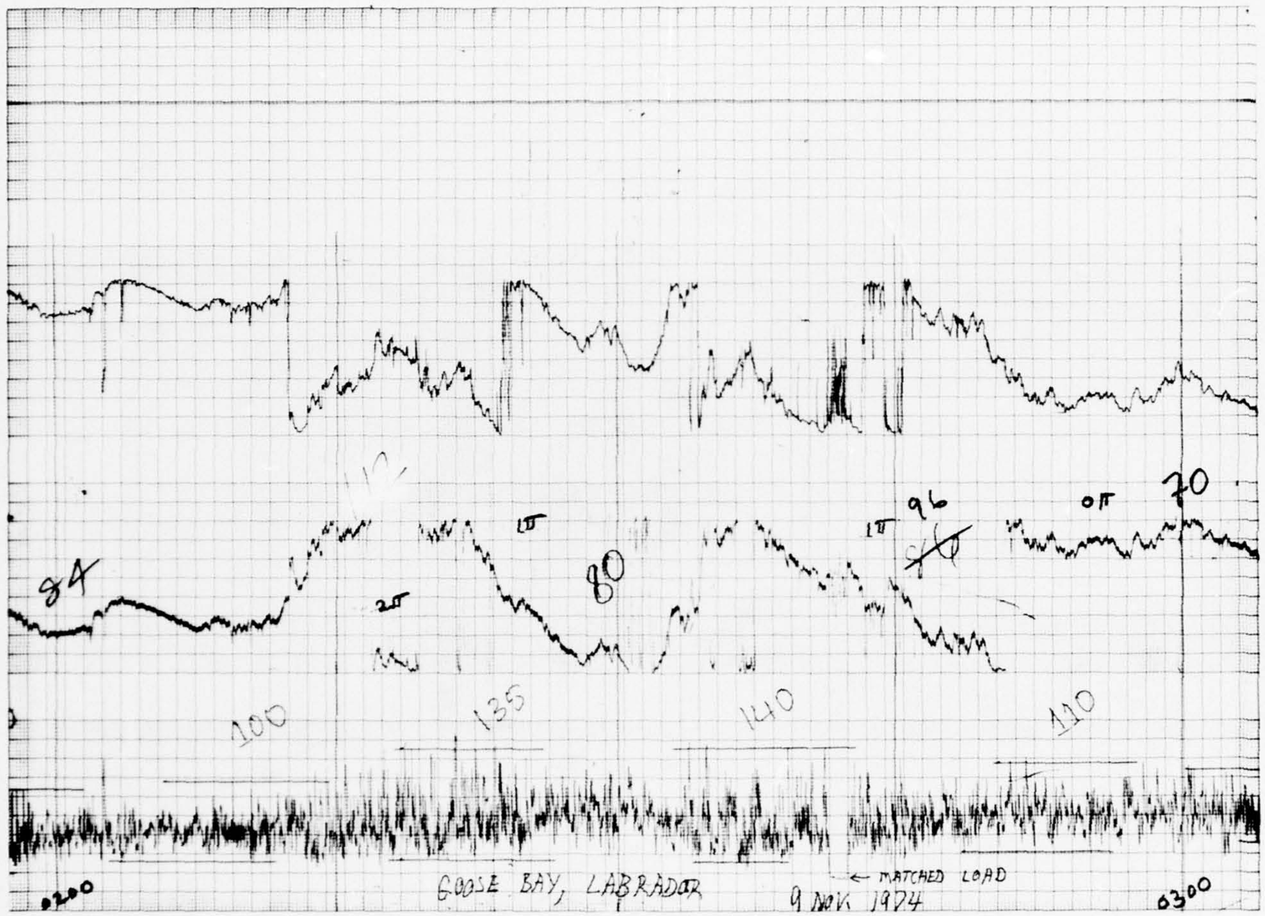

Figure 38. The Rapid Polarization Changes That Result From Auroral Precipitation During a Geomagnetic Storm

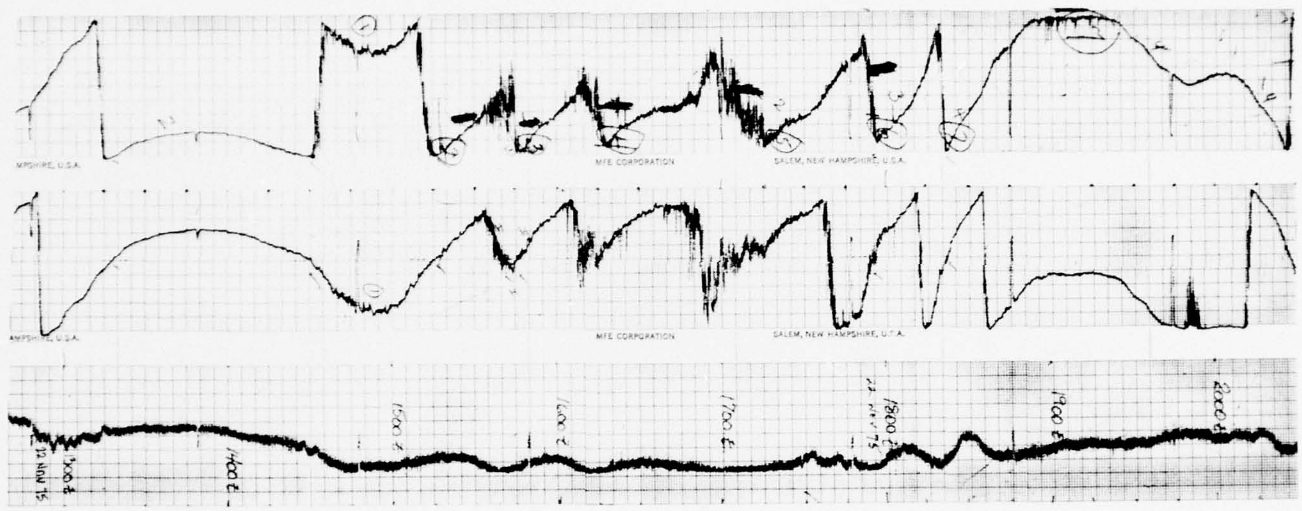

Figure 39. Interference Caused by a VHF Solar Noise Storms

6.10 TEC Recording and Reporting Procedures

A sample of a computer coding sheet is shown in Figure 40. In columns where identical information is carried down the column, the figures need not be repeated. Indicate the continuation of the same character by a wavy line extended down the length of the columns for which data are repeated. Table 4 gives a column by column explanation of Figure 40.

The description of the required format in Table 4 is the standard World Data Center format; AFGL requirements do NOT include the qualifying letters, and do not permit interpolated values. In addition, the descriptive letter "C" is not used. Only blank spaces are left where the value would have been had a measurement been possible. For those stations that send original data back to AFGL for archiving and for use in amplitude scintillation data reduction, the station identification information must be placed on both ends of each chart record sent.

The chart records should be folded into sections approximately 11 in. long so that any portion can be readily examined. Times should be well marked on the record. Only Universal Time is to be used. Local time can be very confusing with the changes to and from daylight saving time and, therefore, no local times are ever used. Remember, the final output of the entire TEC experimental program is only as good as the chart recordings and the computer coding sheets. Taking the necessary care to insure carefully annotated records and carefully checked computer coding sheets is very important and will contribute greatly to the overall success of the TEC program.

Table 4. Column by Column Explanation of Figure 40

Card Column	Description	Remarks
1	Type of card	A "9" indicates that ionospheric values at 15-min intervals are contained on this card.
2	3-hr period of the day	Times from 0000 to 0245 are indicated by a "1". 0300 to 0545 are indicated by a "2", etc.
3-5	Station Code	See master list of station codes or write to WDC-A (Boulder, Colorado) for a new code.
6-7	Year	Last two digits of the year.
8-9	Month	
10-11	Day of month	
12-13	Characteristic Code	"70" Ionospheric Electron Content from Faraday rotation measurements.

Table 4. Column by Column Explanation of Figure 40 (Cont)

Card Column	Description	Remarks
14-18	15-min data entered as twelve 5-column sets	Divided into five columns per 15-min value. First three columns: TEC value in units of 10^{15} electrons/m^2 column, right justified, no decimal point. If the value is more than 999, use M or N Descriptive letter. Fourth Column: Qualifying letter.* Fifth Column: Descriptive letter.†
69-73	Last 15-min value per card	This value is for 0245, 0545, 0845, 1145...2345 depending upon the 3-hr period of the UT day.
74-76	Sub-ionospheric latitude	In whole degrees, no fractions, right justified. Obtain from computer sheets for proper satellite.
77-79	Sub-ionospheric longitude	" "
80	Time standard	"U" is used for Universal or Zulu Time.

*Qualifying letters are: "D" ...... indicates "Greater than"
"E" ...... indicates "Less than"
"I" ...... indicates that a missing value has been replaced by an interpolated value.

†Descriptive letters are: "C" ...... Measurement influenced by, or impossible, for any non-ionospheric reason; e.g., equipment failure.

"S" ...... Measurement influenced by, or impossible, because of interference or atmospherics, including scintillations.

The Descriptive letters M or N are to be used only for TEC data:

"M" To add 1000 to the value reported.
"N" To add 2000 to the value reported.

Descriptive letters "S", "M", and "N" are used when necessary. If both "S" and "M" or "N" are required, only use either "M" or "N" and omit the "S" descriptor.

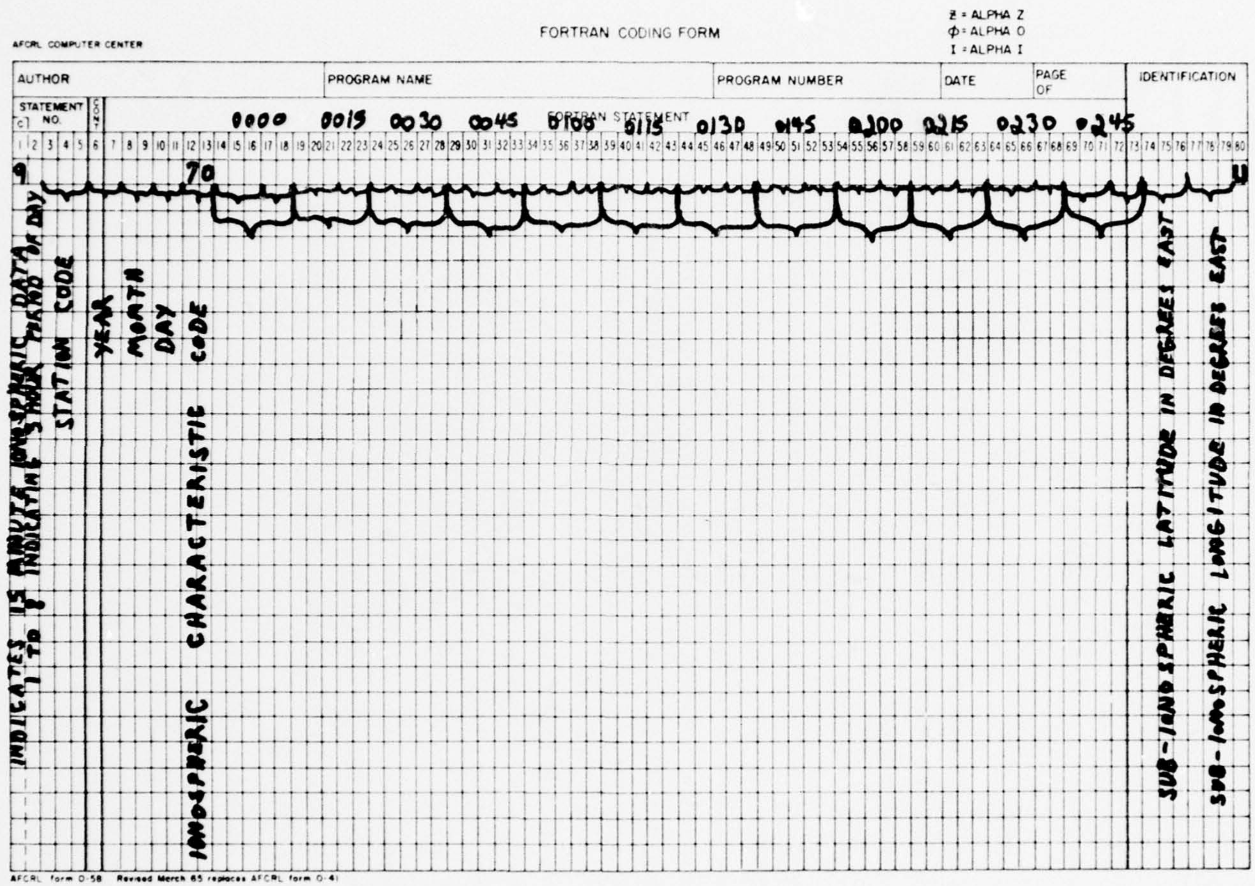

Figure 40. Sample Computer Coding Sheet for 15-min Values of TEC

7. POLARIMETER MAINTENANCE

The commercially built solid state electronic polarimeter recently placed into use at many of the AWS TEC observation stations has been relatively maintenance free, and little of a corrective maintenance nature has been required. However, there are several items that should be checked for preventive maintenance and additional items that should be checked for corrective maintenance before a defective unit is replaced. This section describes those procedures.

7.1 Preventive Maintenance

To maintain optimum polarimeter system performance and correct final values of TEC, the following items of preventive maintenance should be performed on a regular basis, as outlined.

7.1.1 DAILY CHECKS

- Perform relative phase channel calibration as detailed in Section 6.2.1.
- Check receiver tuning. Retune as necessary.
- Check pen heat on chart recorders. Remove any excess wax build-up on the pens by gently scraping pen writing surface with a piece of paper or by turning up the pen heat to maximum for a few seconds to burn off the excess wax. Make certain the pens write properly when this daily check is completed.
- Check chart paper supply.
- Check that time marks are in phase with actual time. Write down date and time at least once per day. Always use Universal Time.

7.1.2 TWICE PER WEEK CHECKS

- Perform amplitude calibration.
- Perform absolute phase calibration.
- Mark calibrations carefully, being careful not to write over the chart tracings.

7.1.3 WEEKLY CHECKS

- Check antenna positioning and physical condition of cables for evidence of wear, corrosion, breakage, water penetration into coaxial joints, etc.
- Remove chart record from recorder and mark end data and station information on the chart.
- Write start date and time on portion of chart remaining on recorder, or on new roll, if new chart roll is required.

Any corrective maintenance that is required, or any time when the chart is not actually recording the satellite signal, should have the reason annotated directly on

the chart record. The chart record is the best data log of what actually happened, and care should be taken to insure that times are correctly written on the chart and any difficulties with the polarimeter system are annotated.

7.2 Corrective Maintenance

The best method for determining whether the polarimeter system is actually working is the amplitude calibration procedure. If the amplitude calibration can be successfully completed, then there is nothing wrong with the polarimeter unit itself and some external cause must be found. The antenna system may have a defective cable, though this can be determined simply by performing an amplitude calibration at the antenna end of the cables, one at a time to determine if they have the same loss. If the calibration works properly but the received signal level is very high, and not tunable, then broadband external interference is the likely cause. Tuning the receiver through the satellite signal should produce chart amplitude changes from the sky level up to the normal satellite level and then down to the sky level as the tuning frequency is changed. If no signal is received, though the amplitude calibration is normal and the antenna cables check out correctly, the satellite is likely off the air.

A word about satellite signal availability is in order. The VHF transmitters on board the geostationary satellites are generally powered by batteries that are charged by solar cells. During the equinox seasons of March and September the satellites are in the earth's shadow for varying periods of time of up to approximately 2 hr, and with older satellites, the batteries can greatly discharge during this time. The satellite transmitter VHF signal output will decrease at local midnight when the satellite enters the earth's shadow and will increase when the satellite emerges into sunlight. Also, the satellite VHF transmitter frequency may change due to the cooling of the satellite during this period. For some of the older satellites, the signal may shut off entirely and may have to be turned on again by ground control. If you see changes in satellite received amplitude during the equinox periods at local midnight, it is likely caused by the above.

If an amplitude calibration cannot be obtained, and the VHF polarimeter receiver seems to be not working, perform the following system checks:

(1) Check all power supply voltages, starting with the a-c primary 115 V regulated output. Check all receiver power supply voltages; in the case of the Aldi Receiver Model 2000, there are three different power supplies. In the AFGL polarimeter adaptor unit, there are also three supplies, and most installations have a separate unit for the VHF converter. Check for the proper d-c voltages, and use an oscilloscope to determine if the a-c ripple voltage is minimal, about 10 mV peak to peak, or less. Bad power supply ripple can cause loss of RF switching coherence and very messy looking phase output on the chart recordings.

(2). If the power supply voltages are normal, check the diode load output of the receiver with an oscilloscope. If the system is working, receiver noise should be visible on the scope. With a strong signal from the signal generator into the system, the diode load should have noise with a sinusoidal 27 Hz switching frequency signal superimposed upon it. If this is not observed with the Aldi system, see the separate instructions furnished with the Aldi units on adjustments of Aldi 2030 Receiver AGC Circuitry. With the AFGL-built system, insure that the receiver RF gain control is not turned too high so that the system is limiting or saturating.

At the output of the 27 Hz switching frequency narrow band audio filter, a good quality sine wave should be observed. With a signal from the signal generator equal to the satellite signal, there should be no evidence of flat topping or clipping of the sine wave. If flat topping of the sine wave is observed, the gain into the filter must be reduced. If the AFGL polarimeter receiver gives some diode output, but the gain is low, the RF converter may not be functioning. Substitition of a spare unit should determine if the RF converter is operating properly. If the phase channels do not give full scale excursions and the phase trace is noisy on both channels, this is an indication that the satellite signal is very weak, or that the receiver noise figure is poor. Check the amplitude channel calibration against previous calibrations, using the same satellite on the same frequency, and determine if the signal from the satellite has dropped in strength.

On rare occasions solar noise storms will occur that produce large increases in solar radio flux at the VHF frequency range. These noise increases can last many hours, or even days, and effectively reduce the signal-to-noise ratio by increasing the noise of the polarimeter system. This type of system problem can be diagnosed by observing that the problem goes away when the sun is well away from the beam of the polarimeter antenna. Unfortunately, nothing else can be done about this problem, which was discussed in Section 6.9.3. A sample of typical data during solar noise storm interference is shown in Figure 39.

If polarimeter power supply voltages check out normally, but no receiver output can be obtained, in the case of the AFGL-built unit with a separate receiver, the tubes in the receiver should be checked, preferably by the substitution method unless one or more tubes have obvious open heaters. The integrated circuits in the Aldi unit are not generally field replaceable or testable. If no signal can be obtained at the output of the diode load of the Aldi unit with proper power supply voltages, the unit must be returned to AFGL or the manufacturer for repair.

If the receiver seems to work, but the polarimeter gives no polarization changes as the phase channels are observed over several hours, check the antenna coaxial cable connections at both ends of the cable. Also perform an amplitude calibration with the signal generator connected to the antenna end of the cables, one cable at a time, to determine if both cables have equal loss. If the cables pass the equal loss

test of having approximately 3 dB of loss per 100 ft, and the antennas look physically intact, the problem may be in the RF switch box itself or in the drive voltages that go to this box. Figure 41 gives the oscilloscope waveforms that should be observed at the inputs to the Aldi RF switch.

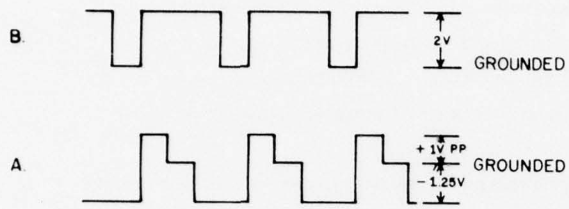

Figure 41. Aldi Antenna Switch Wave Forms

Figure 42 shows the waveforms for the inputs to the AFGL-built switch. The waveforms for the Aldi Corp. RF switch drive are shown in Section V of the Aldi instruction manual. Additional test points on the Aldi include the output of flip-flops on PC boards No. 2, 2', and 2". TP No. 4 (black) should have a 27 Hz square wave that varies in width with polarization change; its amplitude should be approximately 4 V peak to peak.

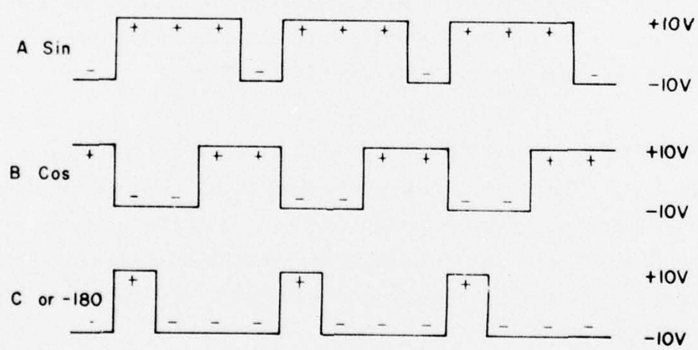

Figure 42. AFGL-Built Polarimeter Antenna Switch Waveforms

Check the output of the filter, cards No. 1 and No. 7, and the junction of R19 and R29 on Board No. 1. You should obtain a pure sine wave with a 27 Hz period. The amplitude should increase with input signal strength. On Board No. 7, this point is pin No. 6 of IC5. The filter on card No. 7 is used for synchronous detection and is deliberately low Q. Thus, its sine wave will be of lower quality than that on Board No. 1.

On the AFGL Polarimeter adaptor, the RF switch waveforms can be monitored at test jacks on the front panel, at least when the switch is not connected. The waveforms can also be monitored directly at the switch, loaded by the conduction of the diodes. In this condition only the back biasing negative voltages are seen. Input and output of the 27 Hz filters is checked from front panel BNC connectors. When adjusting the RF gain of the receiver used in conjunction with the AFGL polarimeter adaptor, the filter output should be monitored to make certain that the output is not flat-topping or limiting in any way. Additional test jacks on the AFGL Polarimeter front panel are: flip-flops for both channels, outputs of the phase integrators, and the amplitude output.

If the switch waveforms are correct and little or no phase change occurs on the chart recordings, either one antenna-driven element may be defective (very unlikely) or the receiver may be tuned to a signal other than that from a satellite that has the same frequency and approximately the same amplitude (also unlikely). If the phase channels give almost full-scale deflections with non-linear ramps and the amplitude channel goes through peaks and nulls in signal, the antenna-cable system is probably at fault and only one antenna is working properly.

Sometimes it is possible to determine if, in fact, the signal is coming from a satellite by rotating the antenna through 90 deg in azimuth and watching the amplitude channel, which should drastically reduce in amplitude.

Pay particular attention to the coaxial RF connectors and the spacing and length of the center pin of the connectors. It is possible that the connector pin does not extend far enough, or may extend too far, to make proper contact with the mating connector without causing damage or a poor connection.

7.3 General Corrective Maintenance Instructions

It is impossible to anticipate every potential fault. The use of standard troubleshooting techniques to narrow down the source of the apparent problem will help greatly, and especially careful use of the amplitude channel and its calibration can help determine whether the source of the problem is within, or outside of, the polarimeter system itself.

The Aldi commercially built system is all solid state, and has given little trouble in service thus far, with the exception of the capacitors in the power supplies.

The AFGL-built system has a solid state polarimeter adaptor unit, but the R-390A receiver generally used with this system contains 25 vacuum tubes that have a relatively shorter life than do solid state components. Fortunately, the R-390A receiver has been a standard military issue receiver for many years and spares are readily available. The standard maintenance book for this receiver should be used

when attempting any repairs to it. Chart recorder problems have included burned out chart drive motors and writing pens.

Operational and maintenance assistance for AWS units can be obtained from AFGL-PHP. With an AWS operational polarimeter, adequate spares are sent with each unit to cover all normally expected maintenance problems.

8. SUMMARY AND CONCLUSIONS

This report has described methods and procedures for the installation, calibration, and maintenance of the VHF electronic polarimeters used in making real-time TEC measurements for the Air Weather Service's real-time polarimeter network. Many of these same methods and procedures apply to groups making similar measurements for later scientific study. Careful attention to the methods outlined in this report will result in excellent quality data for the AWS real-time TEC measurement program and will greatly aid in the scientific studies on the variability of this operationally important parameter. Like any task, the results reflect the care and interest of the individuals responsible for it. This report has been an attempt to facilitate that task, but the rest is up to the initiative of the individual responsible for the operation of the system. Responses to questions concerning any aspect of this work can be obtained by contacting personnel at AFGL's Trans-Ionospheric Propagation Branch (PHP); they will be pleased to help in any way they can.

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